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A Critical Review of Casualties from Non-Combat Submarine Incidents and Current US Navy Medical Response Capability with specific focus on the Application of Prolonged Field Care to Disabled Submarine Survival and Rescue

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14. ABSTRACT

Survival in a Disabled Submarine (DISSUB) event depends upon many variables, one of which is a rapid and appropriate medical response, with assets capable of providing various levels of medical care in a complex and remote mass casualty situation. This report presents an overview of current understanding of risks to survival, existing response capability and initiatives, and develops a phased casualty estimate to support medical loadout planning for Disabled Submarine rescue and surface abandonment scenarios. We identify and suggest mitigation for a number of shortfalls in medical response capability, some of which validate existing R&D efforts and objectives, while others warrant additional SUBFOR operator and medical authority consideration. We specifically explore the relevance of Prolonged Field Care (PFC) capabilities to the DISSUB scenario and to wider submarine critical care / mass casualty incidents, and advocate the application of PFC principles and skillsets to enhance medical response capability.

15. SUBJECT TERMS

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Background

Few USN submarine sinkings have occurred since World War II and none since the loss of USS Scorpion (SSN 589) in 1968, testament to the safety of modern submarine designs and operations. The intervening years have however seen further international losses and continuing occurrence of mishaps that could result in the disablement and sinking of the submarine (a “DISSUB event”). The ongoing risk and high cost of a DISSUB event, together with commitment to international response efforts, make Submarine Escape and Rescue (SER) capability a core safety requirement for submarine operating nations, as further emphasized by the recent loss of the ARA San Juan S-42.

Survival in a DISSUB event depends upon many variables, one of which is a rapid and appropriate medical response, with assets capable of providing various levels of medical care in a complex and remote mass casualty situation. Definition and mitigation of shortfalls in current US Navy DISSUB survival, Submarine Escape and Rescue and medical response capability are current Joint Force, Navy and Submarine Force (SUBFOR) priority objectives.

Research efforts to date have focused on hardware solutions for the DISSUB environment and decompression strategies following DISSUB Escape and Rescue. Examining the epidemiology of DISSUB events and formulating reliable estimates of casualties and threats to the Health Service Support system are critical to effective planning of medical resource requirements.

Prolonged Field Care (PFC) principles offer a novel approach to DISSUB medical response capability gaps. PFC is an established NATO Special Operations Forces (SOF) concept for optimizing survival in austere delayed medical evacuation conditions. It is an existing US capability with agreed potential for extension beyond the operational land environment.

Objectives

To complete a critical historical and scientific narrative literature review and liaise with relevant Commands and Subject Matter Experts (SMEs) to define:

- The clinical and physiological risks to survival and a casualty estimation over time for any DISSUB surface abandonment or rescue event to which the USN may be called upon to provide assistance.
- Required and existing USN DISSUB medical response capabilities from point of injury to evacuation to definitive medical care.
- Skill or equipment advances that could address capability gaps, with particular focus on PFC techniques.
- Recommendations for update of USN DISSUB and surface medical CONOPS and / or IDC training.

Methods

Casualty estimate. We conducted a review of the unclassified historical and scientific literature to support definition of the likely evolution of an international DISSUB rescue or surface abandonment event and an associated casualty estimate. Data sources included Naval Safety Center mishap statistics, historical records, media sources, NSMRL technical reports and proposals (published or archived), PubMed, DTIC, ISMERLO resources, NATO and DoN Instructions and existing submarine rescue and sea survival models.

Capability gap analysis. We collated and reviewed existing Joint Chiefs of Staff Doctrine, NATO and DoN Submarine Search and Rescue policy documents / CONOPS; Submarine Medical Department and Undersea Rescue Command (URC) Authorized Medical Allowance Lists (AMALs) and Naval Undersea Medical Institute (NUMI) Independent Duty Corpsman (IDC) course materials, augmented by discussions with URC and NUMI personnel, to define current USN DISSUB survival and medical management capability from the point of injury through to casualty extraction and onward to definitive medical care. We then critically reviewed our casualty estimate data against existing medical response capability to identify current shortfalls.

Exploration of medical response strategies to optimize survival. Additional literature search and discussion with relevant Subject Matter Experts (SMEs) was undertaken to evaluate advances in medical management capabilities of potential relevance to enhanced survivability in DISSUB surface abandonment and rescue scenarios. We focused on the ten essential PFC capabilities to identify what could practicably and effectively be extended to the submarine force and DISSUB events.

Results

The rate of international submarine and manned, dry Deep Submergence Vehicle (DSV) mishaps which threaten the loss of the vessel has remained largely unabated since the 1950s and, at current rates, would be expected to result in a DISSUB event on average once every 10 years. The vast majority of incidents occur in rescuable waters.

Risk and cause of international DISSUB event

- 64 DISSUB + 148 near-miss events since 1939
- Ongoing risk of adverse events associated with international submarine operations
- Vast majority occur in rescuable waters
- Predominant cause operator error including operator-attributable collisions / groundings and several cases of flooding due to erroneous crew actions
- Risk factors: vessel type; non-mission phase of deployment; sea trials +/- embarked riders

Survivability

- Minority (20%) of historical DISSUB events unsurvivable

- Surface abandonment historically the best option for survival
- Survival prospects worst in systems failures; events caused by flooding and explosion / fire
- Risk factors: trauma; temperature; pressure; atmospheric toxicity (CO_2, hypoxia, CO, N_2, Cl, combustion products); psychological and cognitive effects; survival stores; training.

Casualty estimate

- Biomedical evolution complex with multiple phases and variables. Wide range of outcomes from no / minimal injuries to multiple fatalities: average / worst-case approach to analysis adopted.
- Casualty streams and phasing identified from international historical data
  - Inciting incident: blast/blunt force/head trauma; smoke/burns
  - Post surface abandonment: immersion syndromes; hypothermia
  - Onboard survival phase: smoke/burns; atmospheric toxicity (Cl/CO/asphyxiation)
  - Failed egress >7 days: atmospheric toxicity (CO_2/hypoxia/CO/smoke)
  - Surface rescue phase: blunt force trauma; immersion syndromes; CO_2 toxicity
  - Undersea rescue phase: nil additional injuries
- Additional predicted injuries from published research data
  - Onboard survival phase: cold or heat injuries
  - Undersea rescue phase: Decompression sickness (DCS) and pulmonary oxygen toxicity (POT) post pressurized rescue (>60fsw)

USN capability gaps

- Onboard survival and medical response
  - Atmospheric monitoring, communications and resupply shortfalls
  - Reliability of stay-time calculations
  - Single point of failure for trained onboard medical response
  - Personnel/equipment likely to be overwhelmed
- Topside medical response
  - Ill-defined medical response for surface abandonment
  - Heavy focus on lift and recompression capability
  - Limited space / supplies to treat conventional casualties
  - Lack of standardization / modularization of equipment
  - Limitations of available casualty tracking tool
  - Lack of effective mechanism for onward movement of survivors
- Need for increased focus on surface abandonment and escape capability?

Prolonged Field Care

- Relevant to DISSUB scenario (austere, delayed evacuation conditions; space constraints on medical loadout planning) and casualty streams (blast/blunt force/head trauma; smoke/burns)
- USN Submarine IDC training/med stores already support many PFC capabilities
- Some deficient "minimum" level PFC capabilities with added risk if main medical stores inaccessible

- Use of more advanced PFC skills limited by competency maintenance issues (ultrasound diagnostics; sedation/ventilation; surgical interventions)
- Some basic level PFC capabilities only achievable topside (telemedical support; laboratory)
- Advocated extension of PFC cross-training approach to submarine Emergency Medical Assist Team (EMAT) training.

Data limitations

DISSUB events are thankfully rare and incorporation of a broad timeframe and international data were necessary to support any meaningful analysis. While we have endeavored to provide data break-down and to highlight trends over time, we acknowledge that extrapolation of wide-ranging historical outcomes may not fully reflect the impact on DISSUB survivability of recent or nation-specific advances in submarine design / operations and SER capability. Our population estimates should be used with discretion for risk assessment by individual submarine-operating nations.

1.0 Introduction

Entrapment of part or all of a submarine crew in a disabled submarine (DISSUB) is an established risk of submarine operations in peace and war. Few USN sinkings have occurred since World War II and none since the loss of USS Scorpion (SSN 589) in 1968, testament to the safety of modern submarine designs and operations. The intervening years have however seen further international losses, most notably the BAP Pacocha in 1988 and the K-141 Kursk in 2000. At the time of writing, an international search and rescue operation had recently been mounted for the missing ARA San Juan. USN and international submarine force involvement in major incidents of fire, flooding, collision and grounding and loss of propulsion also continues at an average rate of 1.7 a year, of which over half are considered to have significantly risked the loss of a submarine.[1,2] Analysis of USN mishaps by NSMRL in 2007 showed the rate of mishaps with DISSUB potential to have remained relatively constant since the Cold War.[2,3] The ongoing risk and extremely high cost of a future event, together with commitment to international response efforts, makes Submarine Escape and Rescue (SER) capability a core safety requirement for submarine operating nations.

Although perceptions have been skewed by the 1963 and 1968 losses of the USS Thresher (SSN-593) and USS Scorpion (SSN-589) which occurred in deep ocean, the statistical record shows that the vast majority of all incidents occur in waters shallow enough to allow a submarine to sink to the bottom with a low likelihood of hull collapse and in depths comptible with both DISSUB crew survival and escape and rescue capability.[4] Continuing USN shift towards more littoral-based operations further increases both the risk of collision with shipping and undersea obstructions and the likelihood of an incident being within rescuable waters.

When a submarine sinks, there are three possible means of salvaging personnel. The stricken submarine may remain afloat for a time before sinking following a surface incident, or be able to surface for a period following a submerged incident, providing the crew with an opportunity to evacuate. If damage control efforts fail and the submarine sinks within compatible depths, surviving crew can then either exit the submarine through escape hatches and effect a through-water ascent to the surface or, if onboard conditions allow, they can await rescue by dry transfer to a submersible rescue system. Rescue being the USN-preferred option in most situations[5] and with the potentially extended Time To First Rescue (TTFR) associated with greater remoteness from rescue assets, the US Navy has established a seven-day DISSUB survival capability goal.[6]

Survival in a DISSUB event is dependent on many variables, one of which is a rapid and appropriate medical response, with assets capable of providing various levels of medical care in a complex and remote mass casualty situation. Definition and mitigation of shortfalls in current US Navy DISSUB survival, Submarine Escape and Rescue and medical response capability are current Joint Force,[7] Navy[8] and Submarine Force (SUBFOR)[9] priority objectives.

Medical departments aboard submarines are limited in terms of personnel, expertise and equipment. Every item carried on board has to be justified in terms of storage space and compatibility with the submarine environment. In the US Navy, the Independent Duty Corpsman (IDC) is the medical provider aboard and, as a qualified corpsman, undertakes a further 12 months training at the Naval Undersea Medical Institute (NUMI) before being qualified to serve on a submarine. During this period there is specific training in health physics and atmosphere sampling / control. There is also more advanced medical training so that the IDC can operate independently in remote, austere environments, treating submariners and advising the command with regard to medical matters. The IDC is the sole medical expert and the command relies on their knowledge and advice. The IDC has to maintain their medical core skills while also taking on responsibility for whole boat and specialist duties. Any new knowledge, skill or equipment in a submarine will have implications for the training of the IDC and for skills retention / reinforcement.

DISSUB medical response capability is further augmented by support from mobilized rescue organizations. This will include first responders, major incident medical management assets and specialist response capability including hyperbaric medical expertise. Rescue organization medical response capability encompasses a broader range of knowledge, skills and equipment than those available on a submarine, but space and practicability constraints remain significant and any proposed capability uplift would be subject to similar feasibility and cost-benefit justification. Onward transfer capability to definitive medical care is also a key outcome consideration in any DISSUB survival scenario.

Prolonged Field Care (PFC) is a term adopted by the NATO Special Operational Forces Medical (SOFMED) Working Group and wider nations with SOFMED capability to refer to "Field Medical Care, applied beyond doctrinal planning time lines, in order to decrease patient mortality and morbidity, which utilizes limited resources and is sustained until the patient arrives at an appropriate level of care."[10,11] It has been more informally defined as "Treating a patient that you know should be somewhere else, for longer than you want" (Maj Doug Powell MD, USASOC Intensivist).[12,13] It is essentially an extension of Tactical Combat Casualty Care (TCCC) combat trauma capabilities, developed to optimize survival from all-cause mortality and significant morbidity scenarios arising in remote, delayed medical evacuation situations in the operational land environment. The US military already has PFC capability within the Special Operations Medical community and its adaptability is evidenced by its successful extension to military and civilian wilderness and expeditionary medicine settings. Potential for its further extension to the maritime environment is supported and being actively explored.[12,14-16] With demonstrated effectiveness and practicality in a variety of remote environments, PFC principles and management strategies offer an approach for addressing DISSUB medical response capability gaps.

Submarine Escape and Rescue Capability remains a dynamic technological and scientific field. Research efforts have focused on hardware solutions for the DISSUB environment and decompression strategies following DISSUB Escape and Rescue. Examining the epidemiological features of DISSUB events and formulating reliable estimates of casualties and threats to the Health Service Support system are critical to effective planning of medical resource requirements. The presented work provides a novel focus to DoN DISSUB research efforts.

This paper presents a critical review of the likely biomedical evolution and existing medical response capability in DISSUB surface abandonment and rescue scenarios, with particular consideration of the potential application of PFC Principles to enhance crew survival. Our intent is to collate information to better define DISSUB medical response capability gaps and make recommendations for their mitigation.

We will present an updated assessment of the risk and potential causes of a further international DISSUB incident. We will evaluate the clinical and physiological risks to survival and a casualty estimate over time for any DISSUB surface abandonment or rescue event to which the US Navy may be called upon to provide assistance. We will define required and existing US Navy DISSUB medical response capabilities from point of injury through to evacuation to definitive medical care, and discuss skill and equipment advances that could address capability gaps, with particular focus on PFC techniques. We will finally outline our recommendations for update of US Navy DISSUB onboard and surface medical CONOPS and IDC training.

2.0 Methods

2.1 Casualty estimate

2.1.1 Biomedical evolution and risks to survival

We conducted a narrative review of the published medical and scientific literature to support definition of the likely biomedical evolution and clinical / physiological risks to survival in disabled submarine surface abandonment and undersea rescue scenarios. Data sources included NSMRL technical reports and proposals (published or archived), PuBMed, Ovid, DTIC, ISMERLO resources, NATO and DoN Instructions and existing submarine rescue and sea survival models. Search terms used included disabled submarine; DISSUB; submarine AND disabled; accident; incident; mishap; rescue; surface abandonment; survival; and individual risk factors identified from initial hits.

2.1.2 Mishap data

We collated and categorized international non-combat submarine mishap and available associated casualty data, dating back from July 2017 to the USS Squalus (SS 192) and HMS Thetis (N25) accidents in 1939, into an Excel database. The year was chosen as marking the advent of successful submarine escape and rescue capability. International mishap data was used both to provide sufficient incident numbers to support meaningful analysis and because of its relevance to internationally-organized response efforts.

Mishap data was gathered from various unclassified sources including the following:

- *Literature*. A number of books, book chapters and journal articles have been written on the subject of submarine accidents.[1,17-26]
- *Reports*. Several published reports providing compendia of submarine accidents[4,27-31] were identified.
- *Databases*. Several official[32-34] and unofficial[35-37] databases were found online which incorporated ship / personnel casualty data.
- *Findings of investigations and enquiries* into submarine accidents which have been released into the public domain.[38-40]
- *Training / conference materials* relating to submarine accidents.[41,42]
- *News articles* including editorials[43-46] and contemporary reports of individual accidents.[*]
- *Oral histories* derived from online heritage sites, forums and blogs relating to submarines.[47-49]

Table 1: Applied data categories and definitions

	Inciting incident
Systems failure	Material failure resulting in uncontrolled dive, loss of propulsion or life support systems failure
Reactor accident	Nuclear submarine reactor failure or damage resulting in loss of containment and/or propulsion
Collision	Submarine impact with another vessel, man-made infrastructure or natural undersea obstruction
Explosion / fire	Material or personnel damaged by explosion of onboard ordnance, pyrotechnic or equipment or by outbreak of fire
Flooding	Submarine's watertight integrity compromised by ingress of seawater through open hatches or seq failed / erroneous valve operation
Grounding	Impacting of the submarine on the seabed or shoreline
Snagging	Submarine entanglement in underwater lines or cables
Not known	Type of incident not definitively established
Other	Isolated miscellany including inadvertent activation of fire suppressant system; hydraulic rudder-ram accident and active shooter incident
	Mishap outcome
DISSUB	Mishap results in disablement and uncontrollable sinking of the submarine
Near-miss (external aid requirement)	Submarine remains afloat following mishap but severity of damage or casualties requires mobilization of recovery effort or medical response
Near-miss	Submarine able to proceed under own power and/or manage casualties without external support pending return to port
Near-miss (collateral casualty)	Damage / casualties primarily suffered by other involved vessel / personnel
Injurious mishap	Mishap results in fatalities and / or injuries to crew / collateral personnel
	Survivor egress
Surface abandonment	Evacuation of part or all of the crew while the stricken vessel is on the surface
Surface rescue	Recovery / direct evacuation of part or all of crew to another surface vessel and / or stricken vessel taken under tow
Undersea rescue	Part or all of surviving crew extricated from sunken submarine by dry transfer to a submersible rescue system
Escape	Part or all of surviving crew exit the submarine through escape hatches and effect a through-water ascent to the surface
Failed egress	Survivors of inciting incident who subsequently died onboard sunken submarine before escape / rescue could be effected

[*] various media articles and boat-specific veterans forums identified on Google search for individual accidents using the search terms "boat name AND accident (type)". Not discretely referenced due to numbers.

Search terms used included submarine AND accident; incident; mishap; disabled; fatal*; casualt*; injur*; or more specific incident subtypes e.g., crash, collision, grounding etc. For each identified incident, data attributes including date, name, class, nationality, complement, location, inciting incident, outcome, survivor egress method and where available, vessel damage, fatality, and injured crew numbers, causes and timing were gathered. The inciting incident, outcome and survivor egress categories applied and their corresponding definitions are described in Table 1. The loss of the ARA San Juan in November 2017 occurred following completion of mishap data collection, and is not included in the presented data analysis.

2.1.3 Data analysis

We analyzed the mishap data to define the frequency, cause, outcome and survivability of international submarine mishaps. We then used combined reported DISSUB casualty data to explore the causes and timing of death and injury over the course of international DISSUB events from inciting incident through exposure to the disabled submarine environment to survivor extrication, to try to derive a casualty estimate over time. We used summary statistics (frequency distributions, range and arithmetic means) and graphical representation to describe the data. For DISSUB incidents with survivors, we derived proportional casualty distributions (all incident mean and worst-case single incident crew percentages) for the various injuries sustained, and extrapolated these to derive medical management burden estimates for maximum USN crew complements. Where data was absent or limited, data from wider injurious submarine mishaps and inferences derived from scientific literature review and /or accepted SME opinion were used to augment or refine casualty estimates. For ten cases (across eight incidents) where numerical inference from qualitative report of fatality (one case) or casualty (nine cases) numbers was required to support quantitative analysis, we substituted 5% of the incident total survivor number for the terms “a few”, “several” or “others” and 10% of the incident total survivor number (or, in one case, 10% of the incident total fatality number) for the terms “many” or “multiple”.

2.2 USN capability gap analysis

We collated and reviewed existing Joint Chief of Staff Doctrine,[7] NATO[50-53] and DoN Submarine Search and Rescue Policy Documents / CONOPS,[5,6,54-59] Submarine Medical Department and Rescue Organization Authorized Medical Allowance Lists (AMALs)[60] and NUMI Independent Duty Corpsman (IDC) course materials,[61,62] augmented by discussions with URC and NUMI personnel, to define current USN DISSUB survival and medical management capability and planning assumptions from the point of injury (i.e., the DISSUB-inciting incident) through to casualty extraction and evacuation to definitive medical care. We then critically reviewed our casualty estimate data against existing USN medical response capability to identify shortfalls in current capability.

2.3 Exploration of medical response strategies to optimize survival

Additional literature search and discussion with relevant SMEs was then undertaken to evaluate advances in medical management capabilities of potential relevance to enhanced survivability in DISSUB surface abandonment and rescue scenarios, with particular focus on Prolonged Field Care capabilities.

3.0 Results/Discussion

3.1 Risk and Cause of a Future DISSUB event

Non-combat mishaps that could result in a submarine sinking include catastrophic system failure leading to loss of propulsion and / or partial flood and significant high energy events that threaten the integrity of the outer hull, e.g., collision with other vessels or undersea obstructions, grounding and internal or external explosion. An international total of 212 such mishaps were identified from 1939 to date, of which 64 (30%) resulted in the sinking of the submarine (a "DISSUB" event) and associated search and rescue efforts. As detailed in Table 2, a further 38 of the 148 "near-misses" resulted in onboard fatalities and / or casualties and another 4 resulted in primarily collateral casualties or damage. In 30 of the 148 "near misses", the damage or casualties sustained were severe enough to require mobilization of some form of external medical response or surface recovery effort.

Table 2: International submarine mishap causes and outcomes 1939-2017

Outcome	DISSUB		Near-miss (external aid requirement)		Near-miss		Near-miss (collateral casualty)		All	
Mishap type	**#**	**Injurious**	**#**	**Injurious**	**#**	**Injurious**	**#**	**Injurious**	**#**	**Injurious**
Systems failure	5	5	0	0	4	2			**9**	**7**
Reactor accident	0	0	4	3	8	5			**12**	**8**
Collision	26	24	4	3	52	4	3	2	**85**	**33**
Explosion / fire	10	10	9	7	9	7			**28**	**24**
Flood	16	14	3	2	7	0			**26**	**16**
Grounding	0	0	7	0	26	1			**33**	**1**
Snagging	2	2	2	1	5	0	1	1	**10**	**4**
Not known	5	5	0	0	0	0			**5**	**5**
Other	0	0	1	1	3	2			**4**	**3**
Total	**64**	**60**	**30**	**17**	**114**	**21**	**4**	**3**	**212**	**101**

3.1.1 DISSUB and overall mishap rates over time

Determined international, non-combat DISSUB and overall mishap rates over time are shown in Figure 1 and confirm the ongoing risk of adverse events associated with submarine operations. Particularly when considered against a significant decline in the number of operating submarines from a mid-1990s peak,[26] the rate of submarine mishaps which threaten the loss of a submarine remains largely unabated and, at current rates, would be expected to result in an international submarine / Deep Submergence Vehicle (DSV) sinking on average once every 10 years.

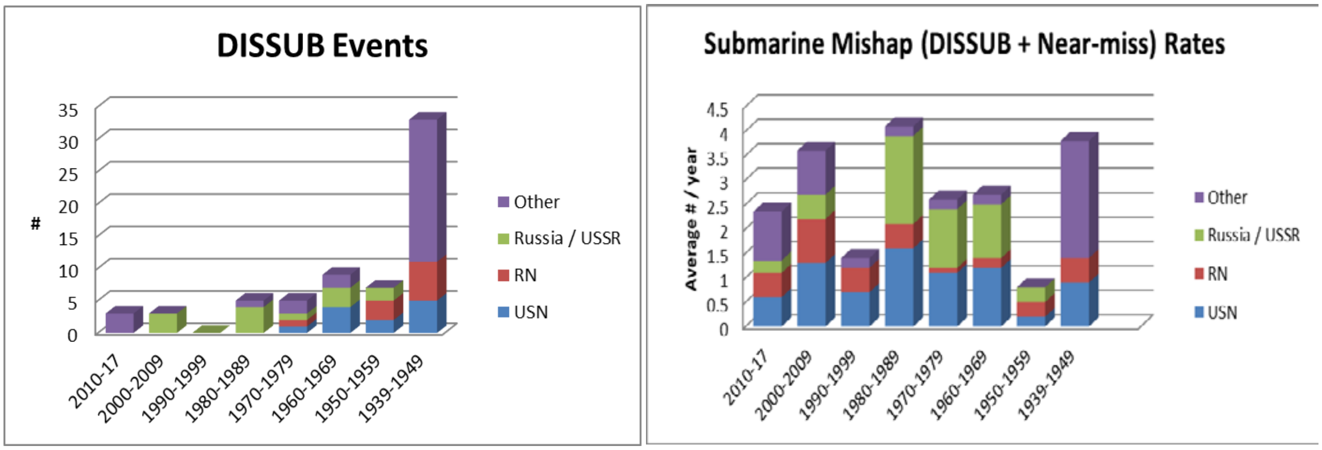

Figure 1: International DISSUB and submarine mishap rates over time

The highest rates of non-combat mishaps and DISSUB events historically coincided with the Second World War (WWII). While this likely reflects the scale of coincident international sea power, spikes in non-combat mishap and adverse outcome rates might be expected in addition to combat casualties during times of major maritime conflict, due to increased operational tempo and constraints on rescue and recovery efforts.

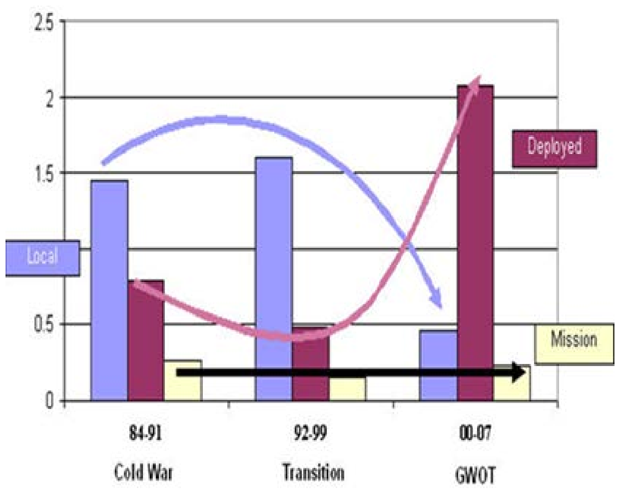

Figure 2: USN submarine mishap rates per 100 ships

A more surprising risk factor was identified in the unpublished previous NSMRL analysis presented in Figure 2 showing that, for the US Navy, almost all serious mishaps over the last 15 years occurred during an SSN deployment, but not while those SSNs were on mission.[2] This implies that operating risks during non-mission times, e.g., transits, are higher than in the past and that risk management is less effective during these non-mission times than during mission execution. This hypothesis would be consistent with recent surface fleet experience and investigation findings[63] and warrants further investigation as a potential focus for risk mitigation in submarine force operations.

3.1.2 Mishap risk by vessel type

Analysis of mishap risk by vessel type is shown in Table 3. The proportions of mishaps resulting in sinking support relative safety of nuclear over diesel-electric (DE) submarine operations. If analysis is limited to currently active classes, the mishap / DISSUB conversion rate is even lower for all but Deep Submergence Vehicle (DSV) mishaps, suggesting further improvements over time and with investment in design and operating safety programs such as SUBSAFE. Meaningful trend analysis is limited by progressively smaller numbers, but this conclusion is supported by published statistical analysis of submarine design safety.[26]

The DSVs included in our data are military and civilian-operated deep-diving manned, dry submersibles, commonly used for research, intelligence and rescue operations. They are typically single or dual compartment vessels operated by a crew of two or three, with little or no onboard living accommodation. They have limited endurance and normally work with mother ships, from which they are launched and recovered. Examples include the Mir, Nautile, Alvin and Priz classes and the Deep Submergence Rescue Vehicles (DSRVs). DSV events were separated out in subsequent analysis due to significant identified differences in cause, outcome and casualty profiles, likely associated with differing design, modes of operation, survival equipment and capabilities, and small crew sizes.

Table 3: Submarine mishap outcome by vessel type

		DISSUB		Near-miss		Total
		n	*%*	n	*%*	
1939-2017	Grand total	64	*30*	148	*70*	212
1939-1958 Pre-nuclear era	Diesel-electric	38	*78*	11	*22*	49
	DSV	2	*100*	0	*0*	2
	Total	40	*78*	11	*22*	51
1958-2017 Nuclear era	Nuclear	9	*7*	114	*93*	123
	Diesel-electric	11	*32*	23	*68*	34
	DSV	4	*100*	0	*0*	4
	Total	24	*15*	137	*85*	161
Active classes	Nuclear	1	*2*	54	*98*	55
	Diesel-electric	1	*8*	11	*92*	12
	DSV	4	*100*	0	*0*	4
	Total	6	*9*	65	*91*	70

3.1.3 Cause of DISSUB events

As illustrated in Table 2 and Figure 3, the predominant cause of DISSUB events (and submarine mishaps in general) is operator error and not system failures. The most common inciting event in nuclear or DE submarine sinkings (n=58) was operator-attributable collision, followed by flooding (of which several were the result of crew valve malalignment, inappropriate running

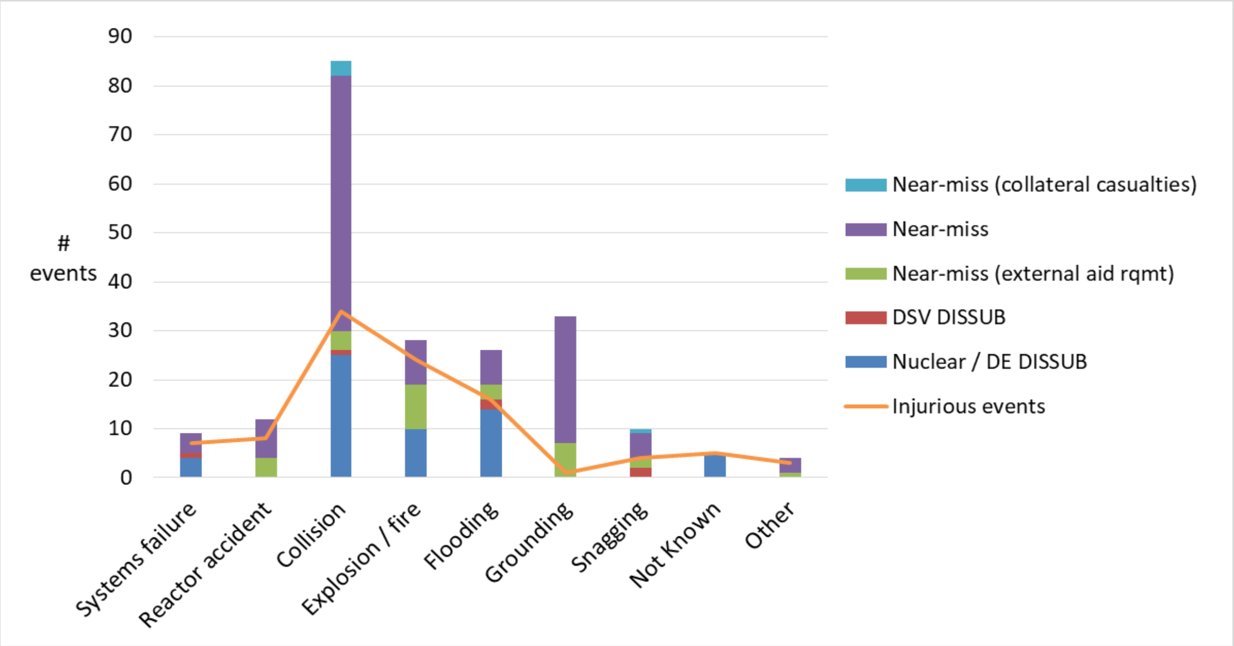

Figure 3: Causes and outcomes of international submarine mishaps 1939-2017

with open hatches or failure to follow procedures); onboard explosion/fire; and dive/propulsion system failure. The cause of sinking was never definitively established in 5 cases. None of the identified nuclear/DE boat snagging and grounding mishaps or reactor accidents resulted in sinking.

For DSV sinkings (n=6), the most common causes were snagging on submerged nets or cables and flooding through open hatches following dispatch / recovery mishaps, which each caused two sinkings, with a collision and a systems failure accounting for the other two.

Considering other risk factors, we noted evidence that the boats involved in at least 14 mishaps, including six DISSUB events and five other mishaps with multiple fatalities, were conducting sea trials and / or had riders embarked at the time. Three suffered systems failures (two catastrophic), while crew distraction, lack of procedural adherence and lack of familiarity of riders with ships systems / survival equipment were recorded as factors in mishap occurrence and severity in others.

3.2 Survivability

Two of the 58 nuclear / DE boats were unmanned at the time of sinking, one under tow and the other alongside undergoing maintenance. Eleven (19.6%) of the 56 manned, nuclear/DE submarine DISSUB events were unsurvivable due either to immediate destruction of the submarine or its rapid sinking in deep water. The corollary is that, contrary to USN experience with the USS Thresher and USS Scorpion, the great majority of sinkings had survivors.

That incidents should predominantly occur in rescuable waters is not unexpected as, even if a submarine patrol is mostly in deep ocean, the most dangerous underway periods are surface and shallow water operations, usually near ports and areas with greater traffic density. Risks of grounding and collision increase significantly and the most hazardous evolutions, such as diving, surfacing, transiting with open hatches and conduct of initial and post-refit trials, are largely conducted in littoral waters.

Table 4: DISSUB crew survival rates in survivable events

	Alive after inciting event (Mean crew %)	Ultimate survivors (Mean crew %)
All cause (n=45)	66.4 (range 9.1 to 100)	46.3 (range 9.1 to 100)
Collision (n=23)	65.7	55.6
Explosion / fire (n=8)	75.9	33.8
Flooding (n=11)	65.3	28.1
Systems failures (n=3)	26.6	26.3

Mean initial and ultimate crew survival rates for the 45 nuclear / DE DISSUB events with survivors are shown in Table 4. Historically, the least survivable events of known cause were systems failures, but this is skewed by the WWII circumstances in all cases, which limited recovery efforts and survival to the 26% of the crew who managed to abandon the sinking boats. Mean initial crew survival rates for other known cause events were broadly similar, but prospects for subsequent successful egress from the stricken boat and ultimate survival were significantly reduced in events caused by flooding and explosion / fire relative to collisions. This is likely due to a combination of higher evident rates of successful surface abandonment in collision events and more significant deterioration in conditions onboard the sunken submarine in catastrophic fire and flooding events.

History has shown that the majority of both nuclear and DE DISSUB survivors have abandoned ship while their stricken vessel was still on the surface (Table 5), but there are inherent risks and availability of survival equipment and early on-scene rescue assets is key. A decline in the predominance of surface abandonment in DISSUB events is also seen over time as illustrated in Figure 4. In two incidents, there was more than one method of survivor egress, with some remaining survivors effecting escape at depth after incomplete surface evacuation of the surviving crew prior to sinking. Surface abandonment was predominantly achieved before sinking following an incident while either surface running or during surfacing operations, but was effected following successful temporary return to the surface following an incident at depth in three of the twenty-seven surface abandonment events where this level of data was available.

Table 5: Method of nuclear/diesel-electric DISSUB survivor egress

Method of egress	Incidents		Numbers attempting	Survivors	Last event
Surface abandonment	All	35	1027	892	2003
	Nuclear	4	291	207	2003
	Diesel-electric (DE)	31	736	685	1988
	[USN component (all DE)	4	180	165	1958]*
Escape	All	11	304	220	1989
	Nuclear	2	92	85	1989
	Diesel-electric (DE)	9	212	135	1988
	[USN component (all DE)	1	14	6	1944]
Rescue	All	1	33	33	1939
	Nuclear	0	0	0	N/A
	Diesel-electric (DE)	1	33	33	1939
	[USN component (all DE)	1	33	33	1939]

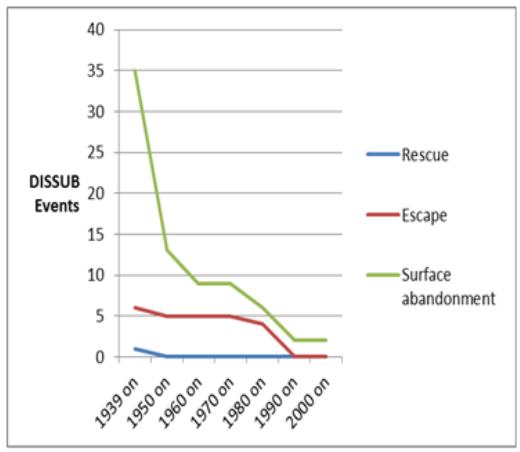

Figure 4: DISSUB Survivor egress over time

While rescue is in itself the safest option, there has to date only been one successful rescue from a disabled submarine, that from the USS Squalus in 1939. 16.9% of all DISSUB crew members who survived the inciting incident subsequently died aboard the sunken submarine, before escape or rescue could be effected. The two DISSUB events involving USN nuclear submarines both culminated in unsurvivable sinking in deep ocean and there is no historical precedent for any egress method in this subgroup.

DSV DISSUB events (n=6) have historically been associated with high rates of both initial (100%) and ultimate crew survival (90.5%), with survivor evacuation primarily achieved through rescue efforts (62% of surviving crew) and otherwise by immediate escape (24%) and surface abandonment (14%).

* Presented survivor egress data is limited to DISSUB events i.e. sinkings. There is additional US experience of successful surface abandonment from a distressed submarine in 1988 (USS Bonefish) and 2002 (USS Dolphin)

3.3 Biomedical evolution and risks to survival

3.3.1 Biomedical evolution

The biomedical evolution of a Disabled Submarine event is complex with multiple phases and potential variables. A schematic overview of the potential evolution of a DISSUB event and associated risks to survival is presented in Figure 5 and will be expanded upon below. We will then provide a more in depth review of current understanding of the factors limiting DISSUB survival, before using the historical and scientific evidence base to develop a more detailed casualty estimate.

An event that causes the sinking of a submarine is likely to be violent and result in injuries to the survivors. Biomedical challenges to survivability and to onboard and rescue organization medical responders would then be anticipated to accumulate with exposure to a variety of environmental, physical and psychosocial stressors over time in a seven-day DISSUB survival situation, and associated potential surface, abandonment, escape and rescue scenarios.

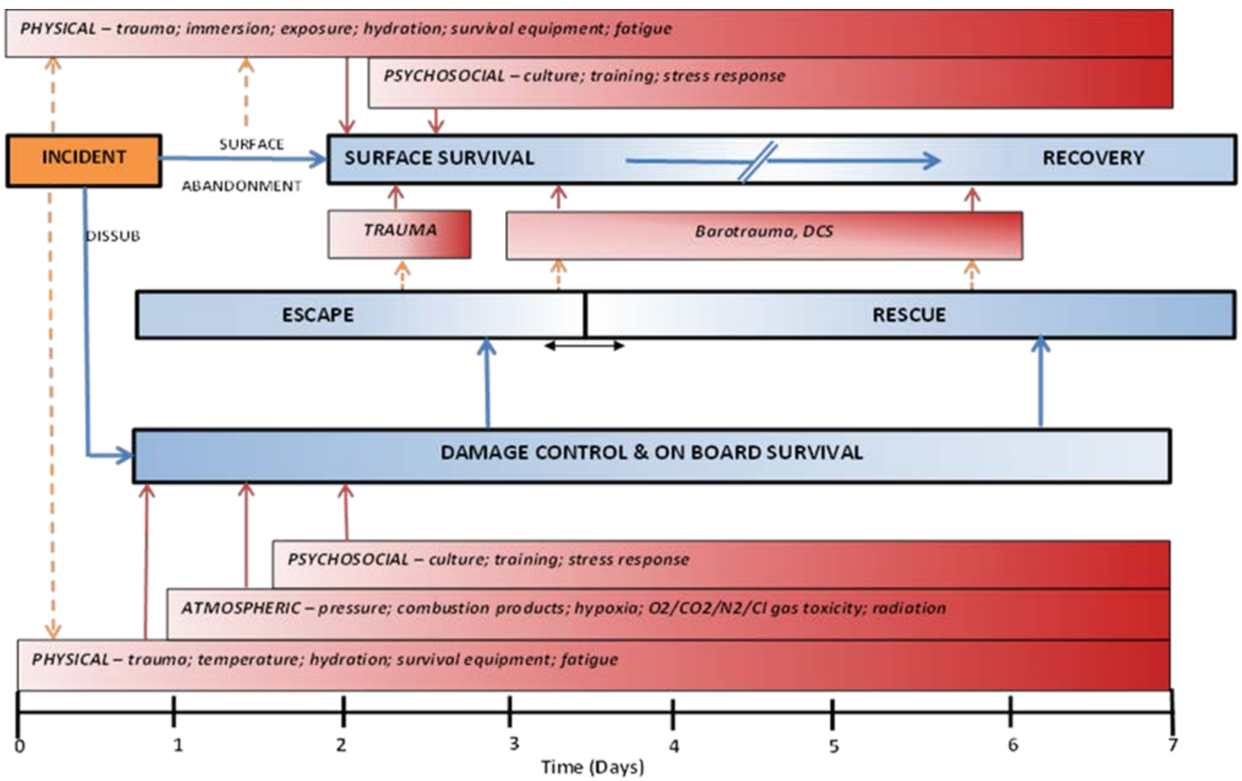

Figure 5. Schematic of DISSUB evolution, Causal pathways and Biomedical factors affecting survivability

[Color gradients reflect *phase transition* and *survival risk factor accumulation / progression* over time]

3.3.1.1 Inciting event

A submarine sinking may result from catastrophic system failure leading to partial flood or by a significant high energy event that breaches the outer hull. Potential causes include collision with other vessels or undersea obstructions, grounding and internal or external explosion. An event that leads to disablement or sinking of a submarine is likely to also cause onboard fires with release of toxic combustion products. Contact of saltwater with submarine batteries may result in release of chlorine gas. In nuclear submarines, reactor damage may expose survivors to ionizing radiation energy or contamination with radioactive material.

System failures may result in few immediate injuries, but other inciting events significant enough to disable the submarine would be anticipated to result in injuries to a proportion of the crew. Injuries to personnel may also result from initial damage control efforts. Immediate injuries might include blast, penetrating or blunt force trauma; immersion injuries; and burns, smoke and toxic gas inhalation; either in isolation or combination.

3.3.1.2 Surface abandonment

The stricken submarine may remain afloat for a time before sinking following a surface incident, or be able to surface for a period following a submerged incident, providing the crew with an opportunity to evacuate. With assistance, even the significantly injured may be extricated. The challenges of sea survival may introduce other medical problems dependent on available survival equipment, on-scene rescue assets, and the delay to definitive recovery. Medical management challenges among survivors would be similar to any other maritime surface abandonment event, including drowning syndromes and potentially widespread seasickness, dehydration, and hypothermia, in addition to injuries from the inciting incident and from potential sea life attack. Forced egress from a submarine through the sail due to low freeboard or high sea state may, however, result in a higher incidence of blunt force trauma cases from associated impacts with the hull or sail.

3.3.1.3 Onboard survival

If damage control efforts are unable to prevent the uncontrolled sinking of a submarine in rescuable waters, the onboard survival phase begins. The disabled, submerged submarine will almost certainly have suffered an uncontrollable flood to one or more compartments, with resultant fatalities. Survivors in the remaining compartments will initiate continual reevaluation of DISSUB conditions to determine whether escape or rescue provides the best chance of survival and safe stay times. The US Navy’s policy is that, if conditions allow, survivors in a submerged disabled submarine should wait for rescue, which can be accomplished by the use of a submarine rescue chamber (SRC) or submersible rescue vehicle and supporting surface recompression system. Available USN rescue assets and capabilities will be detailed further in section 3.4.3. International rescue organizations aim to achieve first rescue within 96 hours of a submarine sinking. Rescue of large numbers of personnel would then take several days from arrival at the DISSUB, subject to sea state, the ratio of uninjured survivors to stretcher cases and survivor decompression obligations.

Survivors will be exposed to a hostile and progressively worsening DISSUB environment for an extended period with a variety of associated threats to their continuing health and survival, including substantially increased atmospheric pressure; the thermal environment; oxygen depletion; atmospheric contamination; restricted food and water; lack of basic hygiene; health issues associated with stasis; fatigue and cognitive and psychological impacts of their exposure. Widespread dehydration, hypo- or hyperthermia and diarrheal illness may be added to original injuries, influencing their survivability, and first responders are likely to encounter significant triage, extrication and medical management challenges.

3.3.1.4 Rescue

Limited treatment facilities and the added biomedical challenges of extended exposure to the DISSUB environment mean that the most seriously injured are unlikely to survive to rescue. The triage policy applied during survivor extrication from the DISSUB is that unimpaired personnel would generally be the first to be rescued to optimize survival of the greatest number. While this will further delay access of the most seriously injured to definitive medical care, significantly reducing the numbers remaining in the DISSUB can ease atmosphere control problems and improve the survival chances of those getting out later. Survivors with significant trauma incompatible with unassisted escape (e.g., major limb trauma) may also survive to be rescued. DISSUB survivors are likely to be in a severely weakened condition and may require transfer assistance to and from rescue vessels to minimize risk of additional traumatic injury. Rescue following prolonged exposure to a hyperbaric environment also introduces its own problems including risk of pulmonary oxygen toxicity and pulmonary damage from atmospheric contaminants at high partial pressures. Whilst rescue enables controlled decompression, DCS is still a risk, especially at greater depths and pressures and with potentially significant demand on recompression assets. Minor traumatic injuries might be incurred during rescue vehicle transfers. Hypo / hyperthermia is an additional risk to rescue vehicle passengers during transit, or if held on the surface in warm climates prior to onward movement through the rescue system.

Consideration also needs to be given to mitigating the addition of responders to the casualty burden. This particularly applies with regard to the decompression obligation incurred by rescue vehicle operators, recompression chamber attendants and DISSUB Entry Team (DET) members – individuals sent with the rescue vehicle for the purpose of providing systems and medical support onboard the DISSUB during the rescue effort.[59,64,65] DET members will also not have the benefit of compensatory physiological adaptations developed by survivors within the DISSUB through gradual exposure to the deteriorating atmospheric conditions and will be at greater risk of impairment on sudden exposure to the DISSUB environment.

3.3.1.5 Escape

If DISSUB conditions do not permit waiting for rescue, immediate or delayed escape efforts may be necessitated. While the most significantly injured are unlikely to be able to escape, Decompression Illness (DCI), Cerebral Arterial Gas Embolism (CAGE), barotrauma and the physical and psychological consequences of DISSUB and sea survival may add to the clinical caseload of responders. More detailed analysis of the escape scenario is outside the scope of this project, but follow-on work is recommended, as escape may be the only means of survival.

In all scenarios, time is a critical factor. Survivors of the initial incident are going to be in their optimal state in its immediate aftermath, with subsequent environmental exposures within the DISSUB pending rescue and following either surface abandonment or escape only posing an increasing threat to continued survivability and an escalating medical management challenge.

3.3.2 Risks to survival

3.3.2.1 Carbon Dioxide (CO_2)

In most scenarios, the limiting factor for survival time within a DISSUB is the capacity to remove CO_2 from the atmosphere.[57,58] CO_2 levels typically average 0.03-0.09% outdoors and in unconfined spaces. Personnel exposed to CO_2 for days can accommodate for the effects of exposure in the 1-3% range, but when levels exceed 3% (0.03 atmospheres absolute pressure (ATA)) for several hours, pathophysiological effects develop, including progressively severe headaches, loss of ability to concentrate, air hunger, sweating, anxiousness, nausea, dizziness, tremors and burning eyes. Above 5%, increasing mental confusion and loss of coordination result. Exposure to 10% (0.1 ATA) CO_2 will result in loss of consciousness and death within a few hours.[57] When the total and the partial pressure are high, CO_2 toxicity is increased by additive effects of oxygen toxicity and nitrogen narcosis.[66]

CO_2 is produced metabolically by the crew and can be chemically scrubbed from the submarine's atmosphere via an exothermic reaction with lithium hydroxide (LiOH). When the boat's scrubbing plant is not available, canisters of granular LiOH can either be placed into an electrically-powered air-blower called a hopper or poured into Battelle curtains which are then hung from the overheads for passive CO_2 scrubbing. It is unlikely AC power would be available in a DISSUB, with associated reliance on passive scrubbing methods. The Royal Navy, Netherlands and Turkish Navies and US Navy Virginia Class submarines have moved to use of more recently developed Micropore Extendair® sheets. These incorporate LiOH into a flat-sheet polymer matrix capable of reducing ambient CO_2 by a factor of 10 within 15-20 mins, with the added advantages of greater compactness, portability, reduced atmospheric contamination with caustic dust and significantly reduced exertional and PPE requirements for deployment.[67] Both Battelle and Micropore CO_2 passive absorption curtains have been shown to work well, and indeed to be more efficient than hopper-powered scrubbing methods, in trials[67] and simulated seven-day survival exercises,[68,69] and are the preferred DISSUB solution for CO_2 removal. Personal soda-lime-based CO_2 scrubbing devices have also been developed to address potential issues of CO_2 peaking and reduced efficiency in low temperature or low humidity environments encountered with absorbent LiOH curtain use,[70] but have not been generally adopted. Further trials of membrane separator technologies for inexhaustible CO_2 elimination capacity have been advocated, but their usefulness may be limited by associated loss of oxygen and other gases.[71]

In a real DISSUB it is anticipated that, with the existing scrubbing equipment in a well-populated compartment, the CO_2 level might be maintained at about 3% Surface Equivalent Value (SEV) until scrubbing capability is exhausted.[72] Once CO_2 scrubbing resources are exhausted and CO_2 levels begin to climb above 3% SEV, survivors should consider escape.[57,58] To minimize the impact of the raised CO_2 levels on critical planning and actions associated with escape, the Guard Book recommends that all survivors should have completed escape before CO_2 rises to 6% SEV (0.06 ATA).[58]

How long CO_2 levels can be maintained at a safe level within a DISSUB will depend upon the capacity of scrubbing devices, the volume of the survivor compartment(s), the number of survivors and their CO_2 production rate (VCO_2). VCO_2 is itself dependent upon survivor diet, activity level, thermal balance and levels of O_2 and CO_2 in the inspired air. A wide range of VCO_2 measurements have been reported in different DISSUB experiments, due to the significant number of variables that influence VCO_2 under DISSUB conditions,[72] which complicates quantification of survival store requirements. Current US Navy submarine life support stores are premised on conservative assumptions, and distribution of supplies in proportion to compartment volume and worst-case compartment manning to optimize survival potential.[6] A policy of enforced bedrest for DISSUB personnel not engaged in essential duties is also implemented to extend the endurance of survival stores, although studies have found a higher than anticipated level of activity even in subjects confined to their bunks.[72,73] This may in part have been attributable to simulated cold DISSUB conditions in older studies. The extent to which survivors would be able to reduce and maintain low metabolic rates in a real DISSUB situation is unknown. Recent research has shown reversible sedation using diazepam and flumazenil to have the potential to significantly lower VO_2 and VCO_2 by 13-15%, but the six-hour lag in ability to follow instructions and ambulate independently and 72 hour delay in return of normal cognitive and physical function following reversal is likely to limit its usefulness in DISSUB survivors.[74] Low dose propranolol has been found to reduce resting VCO_2 by 6.5% and appeared more promising from a cognitive perspective,[75-77] but administration prior to saturation decompression has been found to worsen DCS and increase mortality in a swine model.[77]

The reliability of currently available Analox emergency atmospheric O_2/CO_2 monitoring devices and the ability of current passive scrubbing technologies to maintain a breathable atmosphere over seven days under DISSUB conditions have been demonstrated in US and Norwegian survival exercises.[68,69] Moderately hypercapnic conditions were well tolerated, but the threshold for onset of headache, impaired concentration and asymptomatic increased ventilation rate occurred well below the 3% SEV nominal allowable CO_2 limit for DISSUB conditions.[57,68,72,78] In the terminal phase of a real DISSUB scenario, these effects would be considerably worse and be accompanied by other unpleasant symptoms of increasing toxicity, all of which could impair survivor ability to engage with escape or rescue efforts. Rescue following prolonged exposure to higher levels of CO_2 (>5% SEV) might also precipitate an “off effect”, with accompanying dizziness and vomiting on resumed exposure to normal air.[66]

3.3.2.2 Hypoxia

A minimum partial pressure of oxygen (PO_2) is required to support life and levels will fall as surviving crew breathes the DISSUB atmosphere. Oxygen consumption rates (VO_2) are related to the activity level of personnel. While survivor activity should be minimized as far as possible to reduce VO_2 and VCO_2, resting VO_2 may be increased by as much as 30% in a DISSUB due to hypothermia, stress and damage control or escape efforts.[79] Atmospheric oxygen would also be depleted by any on-board fire. As PO_2 falls from 0.16 to 0.09 ATA, symptoms of hypoxia develop including tachypnea, labored respiration, severe headache and progressive impairment of cognition and motor performance until unconsciousness and death occur as the oxygen approaches 0.09ATA (9%SEV). Below 0.13ATA (13% SEV), the crew loses the ability to function and carry out escape or rescue procedures.[79]

Monitoring of DISSUB O_2, CO_2, temperature and pressure monitoring is provided by portable, battery-powered, ruggedized Analox (SubMkIIP) devices. Accuracy of O_2 measurements, device endurance and ease of use have been confirmed under seven-day DISSUB conditions.[68,69]

Oxygen can be replenished in a DISSUB by combustion of oxygen candles (usually chlorate based), supply from oxygen banks or, as a last resort, by bleeding air into the submarine from air banks. Oxygen bleed is preferred over candle usage to counteract oxygen depletion[57] because it is easier to regulate to variations in consumption and to avoid compartment pressurization and does not add to DISSUB heat load or atmospheric contamination, with safe and effective use demonstrated during US Navy survival exercises. Full banks will provide sufficient O_2 for seven days, but are not fitted on all boats, including VIRGINIA class submarines, or may be unfilled due to torpedo exercises or operational use. Since 2010 review of US Navy survival stores, oxygen bank availability is not assumed and boats are provided with a seven-day supply of chlorate candles, distributed across compartments in the same manner as emergency CO_2 scrubbing equipment.[6]

Oxygen candles can be burned in candle furnaces, one of which is available in each compartment of US Navy submarines, or in stand-alone cases. Candles produce a fixed volume of oxygen and numbers burned and frequency of initiation have to be tailored to atmospheric monitoring results. Burning oxygen candles introduces chlorine and carbon monoxide into the atmosphere which cannot be removed and requires monitoring to ensure safe limits are not exceeded. Heat output of 9500 BTU/candle may also contribute to heat stress.[69] Malfunctions may present a fire or explosion risk (as seen in the Kursk and HMS Tireless (S88) accidents), which the US Navy mitigates by application of storage time and weight constraints for replacement. US Navy survival exercises have verified oxygen candles effectively maintain O_2 levels without significant fire risk under DISSUB conditions.[69]

Bleeding air banks is a last resort prior to donning Emergency Air Breathing Systems (EABs), when alternatives are exhausted, as it only supplies limited oxygen and, since 79% of the air bank is nitrogen, will significantly increase DISSUB pressurization and DCI risk during escape or rescue. A minimum air bank pressure is also required to maintain escape capability.

In a DISSUB, oxygen supplies should be regulated to maintain PO_2 between 0.17 and 0.20ATA. The upper limit is for suppression of fire risk rather than physiological considerations and is well below oxygen toxicity thresholds. Unless rescue is imminent, escape is mandated if PO_2 is decreasing uncontrollably below 0.16ATA (16% SEV), with the last man out by 0.14ATA to avoid risk of debilitation prior to escape, increased DCI risk and sudden fatal hypoxia risk with small further drops. In most DISSUB scenarios, CO_2 toxicity will limit survival more than decreasing oxygen levels.[57]

3.3.2.3. Pressure

During normal operations the internal air pressure in a submarine is maintained at approximately 1 ATA. Experience has shown that a DISSUB is invariably internally pressurized above 1 ATA to some degree.[51] Causes include flooding through open hatches / valves or breaches of the hull; high pressure air leaks caused by the initial trauma; emergency air / oxygen bleed used to maintain a breathable atmosphere; exhaust from open-circuit Emergency Air Breathing Systems (EABs) employed because of atmospheric contamination; and salvage air pressurization used in an attempt to reduce flooding. The degree of pressurization is unpredictable as all of these factors are variable and may co-exist, but the expectation would be of progressively rising DISSUB internal pressure. The range of pressures of concern in a DISSUB has been narrowed to between 1 ATA (i.e., unpressurized) and 5 ATA, which has been accepted as the upper limit of survivability commensurate with achievable time to first rescue and completed rescue, and defined the design limit for current pressurized rescue capability.

While research efforts remain ongoing,[80] no reliable means of reducing the DISSUB's internal pressure has yet been formally tested. Existing pressurized rescue strategies are accordingly focused on mitigating the key problems resulting from DISSUB internal pressurization: decompression obligation and toxicity of inspired gases.

Decompression obligation

Exposure of the DISSUB crew to increased atmospheric pressure will result in the continuing uptake of inert nitrogen gas from inhaled air into the blood stream and tissues until they are "saturated" i.e., the nitrogen in the blood is equilibrated with the higher partial pressure of nitrogen in the submarine. Once nitrogen uptake exceeds a certain point, crew incur a decompression obligation i.e., they must be returned to normal air pressures ("decompressed") in a gradual, controlled manner in order to keep the inert gas in a dissolved state during elimination from the body. If they are brought back to surface pressure rapidly, the nitrogen may come out of solution and form bubbles in their tissues. These bubbles can disrupt tissue function by a variety of pathological mechanisms, giving rise to the manifold symptoms and signs of decompression sickness (DCS). DCS is commonly subdivided into 2 types. Type I DCS involves cutaneous manifestations or pain (usually in the joints) as the only symptom; type II involves neurological and circulatory symptoms which can lead to life-threatening complications or permanent neurologic injury.

Safe decompression time to minimize DCS risk is exposure (pressure and time) dependent but runs to many hours once individuals reach saturation, even with exposure to relatively low atmospheric pressures. As the 12-24 hours of exposure needed to reach saturation is well within anticipated TTFR, DISSUB crews are expected to be saturated at the point of rescue. Studies have shown that humans saturated at pressures not exceeding 1.7 ATA (an Equivalent Air Saturation Depth (EASD) of 20 fsw) can be directly returned to 1 ATA safely with a low risk of DCS.[81,82] Personnel exposed to pressures exceeding 1.7 ATA for any extended period will incur a decompression obligation which must be met to safely return them to normal atmospheric pressure.[81] Without recompression support, predicted DCS risk to survivors rises rapidly with saturation pressure above the 1.7 ATA threshold, reaching 20% at 2 ATA (35 fsw); 50% at 3 ATA (70 fsw) and 80% at the assumed maximum saturation pressure of 5 ATA (132 fsw internal pressure).[83]

Toxicity of inspired gases

Compression of the submarine's atmosphere will additionally increase the partial pressure of all component gases. As biological effects of gases are generally proportional to their partial pressure as opposed to their fraction, the effect of any component gas in the DISSUB atmosphere will be amplified by pressurization. For example, the biological effects of 2% CO_2 at 5 ATA will be roughly equivalent to the effects of 10% at 1 ATA. The toxicity of atmospheric contaminants will increase with increasing pressure and if there is significant, uncontrollable contamination in a pressurized DISSUB, it will likely result in the crew's demise long before rescue can occur.[81] In addition to DCS risks, nitrogen exerts a narcotic effect at high partial pressures. While there is variation in individual susceptibility, nitrogen narcosis is generally relatively mild at 5 ATA. Associated performance decrements are unlikely to significantly affect survival actions and rescuees can be expected to be fully adapted by the time rescue is effected. Euphoric effects might even be beneficial to crew morale. Performance impacts may, however, be more significant for any complex unfamiliar tasking required of rescue submersible operators.[84]

The major consideration for pressurized rescue operations is the effects of hyperbaric oxygen exposure on survivors. While oxygen is essential for life, in large quantities it can be highly toxic. Prolonged exposures to high fractions or partial pressures of oxygen will cause progressive respiratory symptoms and decrements in pulmonary function culminating in life-threatening pulmonary inflammation, edema, and irreversible fibrosis. A protective effect of nitrogen on rate of symptom development (but not ultimate effect) has been shown, but this is reduced at higher exposures, such that the effects of breathing air at 5 ATA (PO_2 1.05) are equivalent to breathing 100% O_2 at 1 ATA.[85,86] Numerous studies have indicated the threshold for the onset of pulmonary oxygen toxicity (PO_2T) to occur at a PO_2 of 0.5 ATA. Above this threshold, the incidence and severity of toxicity will vary with the PO_2 and exposure time.[59] Oxygen toxicity was originally thought to be a defining factor for survivability to rescue at DISSUB air pressures of greater than 5 ATA. Navy dive experiments (SHAD[87] and AIRSAT[88]) have since shown that the pulmonary effects from compressed air exposure are not as severe as originally thought and that, coupled with ability of rescuees to breathe down the oxygen content of DISSUB survival compartments, pressurizations of 5 ATA and higher should be survivable for periods of at least 48 hours, with complete recovery from the toxic effects of oxygen. Nearly all survivors would, however, be expected to exhibit symptoms and signs of oxygen toxicity with greater than 12 hour exposure to air at 5 ATA. A portion of the crew may be sufficiently symptomatic to require assistance or special consideration following rescue. Complete recovery, particularly of fatigue symptoms, can be expected to take days and even weeks in some crew members.[86,88]

Reliable definition of the pressure-time relationship to rate of development of oxygen toxicity has presented an enduring problem. Empirical limits for oxygen exposure have been developed and form the basis for planned management of oxygen toxicity risk in DISSUB rescue operations.[59,89-91] Risk assessment is, however, complicated by significant variation in individual susceptibility,[88,89,92,93] and identification of non-invasive biomarkers for real-time PO_2T detection and mitigation is an ongoing research objective, with current focus on exhaled Volatile Organic Compounds (VOCs).[94-96]

While rescue allows for controlled decompression, safe, efficient pressurized rescue presents technical challenges. Neither military nor commercial saturation diving communities use air or nitrox for saturation diving and pressurized submarine rescue capability required development of dedicated decompression schedules. Adequate decompression to prevent permanent injury and death takes time. Decompression with a low risk (5%) of DCS takes 14-16 hours from a DISSUB internal pressure of 33 fsw, rising to over 57 hours from 132 fsw.[83] This significantly exceeds rescue submersible turnaround times and, if survivor numbers exceed decompression system capacity, will delay the rescue cycle and imperil survivors who remain exposed to the hazardous DISSUB environment. A variety of strategies to address this issue have been explored: The level of tolerable DCS risk may vary with the circumstances and probabilistic models have been developed which have shown that considerable DCS risk reduction can be achieved with a modest amount of staged decompression. These models provide rescue commanders with a risk assessment tool for balancing DCS risks of incomplete decompression against optimized rescue tempo.[97,98] Latency in onset of DCS after incomplete decompression may also afford opportunity for transport or other interventions to reduce morbidity.

Efforts have also been directed at development of more rapid means of decompressing rescuees, including definition of safe upward excursion limits from air saturation[99] and exploration of isobaric shift of survivors onto inert gas breathing mixtures.[100] The primary focus has been development of accelerated oxygen decompression capability. It is well-established that oxygen decreases decompression time by accelerating elimination of inert gas from the body, but its use in pressurized rescue is complicated by both technological capability limitations and oxygen toxicity risks, including pulmonary and additional CNS manifestations of associated exposure levels. The effectiveness of oxygen pre-breathing (OPB) at saturation, intermittent high inspired oxygen during staged decompression and combined approaches for reducing decompression time from saturation exposures have been demonstrated experimentally, with manifest oxygen toxicity considered within acceptable limits for emergency use.[101-106] Minimum safe accelerated oxygen decompression schedules have consequently been developed[102] and incorporated into US Navy SRS decompression plans.[59] Their implementation is however subject to oxygen delivery capability and the condition of survivors, both of which present ongoing issues. The schedules are premised on fit, healthy subjects. If DISSUB survivors have already had significant oxygen exposure prior to rescue, or have sustained lung damage from other DISSUB atmospheric contaminants, they may not be able to tolerate oxygen decompression. Current research is focused on definition of the pathophysiological mechanisms of oxygen toxicity and identification of pharmacological solutions to mitigate oxygen toxicity risk and facilitate tolerance of accelerated decompression. A potential SRDRS oxygen delivery system has been developed[107,108] but technical concerns continue to preclude its acceptance into service. The unvented nature and difficulties of managing O_2 toxicity, particularly seizures, in the confined space of the PRM also currently preclude OPB capability during transit to the recompression facility.

Pressurized rescue submersible technical limitations and the need to maintain repetitive rescue capability and tempo require transfer of survivors to a deck decompression facility. Associated risk of DCS has been minimized by development of Transfer Under Pressure (TUP) capability, where the rescue vehicle and recompression facilities are directly connectable and allow rescuees to be held at saturation pressure during transfer. If TUP capability is not available, rescued submariners will be exposed to a rapid fall in pressure during the Surface Interval (SI) between arrival at the surface and transfer / transport to a recompression facility. The safe surface interval decreases with increasing pressure exposure, falling to 15 minutes for Equivalent Air Saturation Depths (EASDs) of 25-60 fsw and 10 minutes for EASDs of 60-75 fsw.[97] Beyond this range, surface excursions would be expected to result in some cases of decompression sickness. Deck chamber transfer times of under 10 minutes are only likely to be achievable by limitation of numbers of personnel rescued per run.[24] If the recompression facility is located on an adjacent platform rather than co-located on the Vessel of Opportunity (VOO), up to 45 minutes could be required for transfer of a full rescue submersible complement.[59] Procedures have been developed using a period of OPB to extend the safe surface interval, but they are subject to O_2 delivery and toxicity constraints, are untested experimentally, and the associated risks are not known. They are advocated for emergency use only and no credible procedures have been developed for EASDs deeper than 90 fsw.[59] Coordination of triage and trauma interventions in injured survivors,[109] and managing operator and DET team risk and decompression requirements[64,65,110] present further challenges to pressurized rescue planning.

Controlled decompression from saturation conditions in a disabled submarine scenario is not always an option. If adequate TUP or recompression facilities are not available following rescue from a pressurized DISSUB, or their capacity is exceeded, rescuees may suffer from severe or fatal decompression illness. Additional research has been directed at quantifying the risks of a bad outcome to support triage decisions[111] and identifying prophylactic, non-hyperbaric methods of mitigating the risk.[112-115] Addressing the various challenges of pressurized submarine rescue is a significant area of ongoing research and development.

3.3.2.4 Atmospheric contaminants

There are multiple potential sources of atmospheric contamination in a DISSUB. A catastrophe that results in a DISSUB is likely to produce supplementary damage such as fires, flooding, saltwater contamination of the battery, and system ruptures or leaks. Human metabolic process may lead to build up of toxic metabolites, particularly if large numbers of survivors are confined in a single or small compartment(s). Efforts to maintain a breathable atmosphere may give rise to other contaminants, through caustic LiOH spillage or dust generation and release of carbon monoxide and chlorine by-products of chlorate candle usage. There are no available technologies for reduction or removal of atmospheric contaminants from a DISSUB. Following a submarine sinking, checks of all accessible systems and containment of any damage or spillages should be effected as quickly as possible to minimize development of toxic atmosphere levels and regular atmospheric monitoring should be initiated.

Seven contaminant levels guide US DISSUB survival and escape decisions and are premised on particular concerns regarding potential for release of combustion products from on-board fires (carbon monoxide (CO), hydrogen cyanide (HCN), hydrogen chloride (HCl), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and ammonia (NH_3)) and for release of chlorine gas (Cl) in the event of saltwater contact with the submarine’s batteries. CO and HCN are asphyxiants, the other five are irritant gases with additive effects. Biologic effects are usually proportional to their partial pressures.

The US Navy has developed Submarine Escape Action Levels (SEALs) for each of these toxic gases for the purpose of protecting survivors from adverse health effects and minimizing requirement to wear Emergency Air Breathing systems (EABs) and associated accelerated pressurization of the boat.[116] SEALs define the maximum concentrations of a gas in a disabled submarine below which healthy submariners can be exposed, without respiratory protection, for up to 10 days (SEAL1) and 24 hours (SEAL2) without experiencing irreversible health effects. Cumulative Effect Indices (CEIs) are additionally derived to take into account the additive effects of the irritant gases, effectively lowering the SEAL1 and SEAL2 for each gas when mixtures are present.

Exposures below SEAL1 and 2 might produce moderate, reversible effects such as irritation of the skin, eyes or respiratory tract and central nervous system (CNS) effects, including headache, visual disturbance, decreased manual dexterity, difficulty concentrating, syncope, nausea and vomiting, but will not impair respiratory or CNS function to the extent of impeding ability to escape or be rescued, or to perform specific survival tasks such as shutting off a valve or using a fire extinguisher. Above SEAL1, the atmosphere is still breathable for 24 hours without wearing

EABs, unless contaminant levels reach or exceed SEAL2 or associated CEI thresholds, in which case all personnel must immediately don EABs to avoid risk of significant functional impairment and potentially fatal exposure. Efforts should be made to control or contain the contaminant source and some reduction in toxic gas concentrations may result over time from adsorption onto submarine surfaces or solubility in water. Atmospheric surveys should be repeated periodically to allow the earliest possible discontinuation of EAB use. SEAL limit excess and EAB usage would also be among the parameters used to inform decisions to await rescue or initiate escape.

SEALs have some acknowledged limitations. They are premised upon an atmospheric pressure of 1 and a temperature of 25 degrees C and corrections for temperature and pressure may need to be made for prevailing DISSUB conditions. Due to lack of data, they do not account for the effects on gas toxicity of factors such as ambient pressure, oxygen and carbon dioxide concentrations, the presence of airborne particulates, the number and physical condition of survivors, variations in individual susceptibility, or potential for acclimation. They are also predicated on a healthy young male submariner population and do not incorporate an uncertainty factor for hypersusceptible individuals, including asthmatics, because this is a disqualifying condition for submarine duty.[116] Riders, who are likely to be demographically different and are not routinely medically screened, may accordingly be more vulnerable to DISSUB toxic gas exposures. Rescue force DISSUB entry teams may be similarly more affected and additionally lack survivor acclimation associated with chronic exposure.

The other significant problem with DISSUB toxic gas management is dependence on unreliable chemical detector (Dräger) tube technology for assessment and monitoring against SEALs. The tubes are known to have a limited shelf life, to degrade under high and low temperature conditions, and to be inaccurate, with risk of cross-sensitivity to gases other than that being measured. Measurements require subjective assessment of color change and extent. Manufacturers and users report variability in measurements of up to 30%,[116,117] with reliability further affected by temperature and humidity and atmospheric pressure.[117,118] These problems may be compounded by user' inexperience and visual compromise[119] under the low lighting conditions likely to be encountered in a DISSUB. The improved monitoring of DISSUB contaminants is a recognised US Navy priority requirement and efforts are underway to develop and transition into service a hyperbaric toxic gas monitor ("SubTox") to more effectively monitor, under pressure, the gases for which SEALs have been defined.[117]

No SEALs are defined or real-time monitoring capabilities available for a range of other possible atmospheric contaminants, including smoke and those arising from system ruptures / leaks, e.g., refrigerants, fire suppressants, AC system coolants, bottled gases, stowed chemicals and weapon propellants. The potential for release of hydrogen gas through seawater contact with the batteries is a current particular concern and is subject to ongoing risk assessment.

To mitigate for imprecision of atmospheric monitoring and inability to measure all potential toxic exposures in a DISSUB, US Navy instructions allow for symptomatic assessment of risk.[58]

Individual crew members are permitted to use and remain on EABs if symptoms are severe and persistent on attempted hourly removal. If the number of survivors on EABs at any one time exceeds a 30% threshold, the crew should proceed as if SEAL2 limits had been exceeded.

In the particular case of carbon monoxide exposure under pressurized DISSUB conditions, removal from the DISSUB environment and return to breathing normal air may aggravate rather than ameliorate symptoms, due to risk of hypoxia on sudden drop in the partial pressure of oxygen which had been maintaining oxygenation of the blood.[97]

3.3.2.5 Thermal injury

In a majority of cases, the DISSUB will be without a significant source of electrical power and / or environmental control. Historical precedent (USS Squalus) and scientific projections had originally predicted that the internal DISSUB environment will cool to the temperature of the water surrounding the boat within 48 hours.[120,121] This would be in the order of 4°C (39°F) on the continental shelf in most parts of the world and it was anticipated that the major thermal hazard on-board a disabled submarine would be threat of hypothermia and cold injury. Relative Humidity (RH) would be expected to rapidly increase towards 100% as a result of the cooling atmosphere and the large amount of water released into the atmosphere by survivor respiration and the chemical reaction between CO_2 and the currently used LiOH scrubbing agent. Vulnerability to hypothermia would be further increased by reduced thermal insulation of clothing from flooding and rising humidity, and in compartments with restricted access to food and / or additional insulation.[72,122] Normal thermoregulatory responses to cold (shivering and peripheral vasoconstriction) may also be blunted under hypoxic, hypercapnic DISSUB conditions,[72,123] although evidence for this is mixed and predominantly relates to more severe, acute exposures.[72] Respiratory heat loss associated with shivering may be significantly elevated under conditions of elevated atmospheric pressure.[84] Cold-induced shivering may itself threaten crew survival times, through accompanying 3-4 fold increase in O_2 consumption and CO_2 production.[124]

Subjects exposed to experimental 4ºC internal DISSUB temperatures, with[123,125] or without[122] accompanying hypercapnic / hypoxic conditions, experienced discomfort but were able to maintain thermal balance and survive for at least seven days with access to adequate insulation (dry clothing or SEIE suits). Thermal stress was primarily manifest as decreased peripheral skin temperatures sufficient to cause non-freezing cold injury, but not any functional impairment of survival or escape activities. Experimental findings suggest that the rate and extent of any temperature drop under DISSUB conditions may be less severe than suggested by modeling assumptions. French (1991), Swedish (1995) and Norwegian (2004) survival exercises in 4-8°C (39-46°F) water recorded interior temperature stabilisation at around 14°C (57°F), with maintained RH of 95-100% in the French experiment and 60-75% in the other two.[68] The Norwegian experiment demonstrated significant diurnal temperature variation coincident with crew activity levels. These experiments showed that, with access to adequate clothing and around 2000kcal a day, DISSUB crew can survive without developing hypothermia or peripheral cooling that would disrupt crew safety or performance.[68] This may not be the case for survivors in compartments without access to food or additional insulation.

Recent historical and experimental evidence suggests that, even in temperate waters, DISSUB survivors may in fact be subjected to progressive temperature rise and heat stress conditions. In the BAP Pacocha disaster, internal temperatures rose from 70 to 77°F (21 to 25°C) in spite of an estimated water temperature of only 52°F (11°C). A 2003 US Navy seven-day DISSUB survival exercise in 37-41°F (3-5°C) ambient conditions recorded a progressive increase in internal temperatures from 70°F to nearly 80°F (21 to 26°C), with mean compartment RHs of 71-81%. An equivalent exercise in warmer waters with ambient temperatures averaging 59°F (15°C), saw internal temperatures rise linearly from 75 to nearly 85°F (24 to 29.5°C) and humidity from 60 to 85% RH over 4 days and the experiment was abandoned at this stage due to heat injury risk. These findings are likely attributable to significantly larger simulated survivor numbers than in earlier experiments and design improvements in hull insulation which had not been factored into modeling assumptions. The major sources of heat were metabolic heat production (350-800 BTU/hr), Battelle curtains (8000 BTU/curtain), chlorate candles (9500 BTU/candle) and emergency lighting (4100 BTU/hr). Residual heat from piping and machinery was associated with an elevated heat stress risk in unventilated engine spaces. It is consequently predicted that temperatures will rise in any DISSUB scenario, unless survivor numbers are small and chlorate candles not needed.[69]

The rate of temperature rise depends upon the nature of the disablement, the submarine's design, level of occupancy, water conditions, and location. Resultant sailor heat strain is subject to DISSUB humidity levels, activities, clothing, and body habitus. Predictions of sailors' thermo-physiological responses incorporating many of these factors have been developed to help guide rescue and planning operations.[126] Ability of crewmembers to mitigate heat in a DISSUB (other than by escaping) are limited,[127] but might include opening scuttles, flooding torpedo tubes or changing placement of curtains. Behavioural measures such as minimizing activity to reduce metabolic heat production and changing to lighter attire should be employed. The effectiveness of physiological evaporative heat loss mechanisms and associated safe stay times will be progressively reduced with rising DISSUB humidity.[126] Heat acclimatization is slow to occur and not apt to provide physiological adaptation to DISSUB conditions in the seven-day escape / rescue timeline.[126,127] Potable water and food supplies on-board US boats should be sufficient to maintain hydration and delay onset of hypotensive and other symptomatic effects for large numbers of survivors under hot conditions,[58,127] but may not be adequate to support advocated limb / extremity immersive personal cooling strategies.[127] Restricted access to food and water may compound heat stress risks in aft survival compartment situations.

DISSUB medical supplies would be quickly consumed by even a few heat casualties. As heat injuries tend to occur in clusters, a large proportion of the crew could be incapacitated in a very short time. It has accordingly been advocated that heat injury risks and particularly the onset of heat casualties should be significant factors in on-board survival decision making.[127,128] Escape planning under such conditions will also need to consider the significant acceleration of onset of thermo-regulatory failure after donning impermeable escape suits.[126] DISSUB heat stress risk assessment modalities[126,127] and escape limits[127] have been proposed, but have yet to be incorporated into US Navy or NATO policy / CONOPS.

3.3.2.6 Psychological and cognitive factors

The DISSUB environment may produce symptoms, e.g., headache, nausea, lassitude or decrements in cognitive function, which could impair survival decision-making and ability to co-operate with survival and rescue efforts. The range of potentially responsible factors is wide and includes overlapping physiological and psychological effects: hypercapnia, hypoxia, oxygen toxicity, nitrogen narcosis, atmospheric contaminants, cold, isolation, darkness and lack of training, all of which can be fatal impediments to survival.[4] Heat, humidity, inadequate lighting, headache, muscle soreness, caffeine / nicotine withdrawal, LiOH dust irritation, discomfort associated with SEIE suit or EAB use, and inadequate sleep (in spite of ample opportunity) have all been reported during DISSUB survival exercises[68,69,72,78] and been shown in previous studies to interfere with cognitive performance.[69]

Heightened arousal and (self-rated) emotional stress which could lead to suboptimal performance and teamwork were identified in the first 24 hours of one survival exercise. It was postulated that DISSUB crew might particularly benefit from extra help with problem solving and decision making support, including checklists and computer-based support, over this period.[129] Tests of cognitive ability under simulated DISSUB conditions have otherwise failed to demonstrate significant performance decrements.[130,131] However, ethical constraints limit simulated physiological exposures to milder anticipated DISSUB conditions, while subject knowledge that conditions are simulated, of short duration and that they are free to leave the trial at any point removes the psychological stress of not surviving. Efforts should be continued to increase understanding and mitigate risks of cognitive impairment in DISSUB survivors. Exploration of prophylactic measures to mitigate other risk factors should also consider cognitive impacts.

The extent to which people are psychologically prepared for disaster and their psychological response to it can affect chances of survival.[132] The prospects for survival increase significantly if a survivor reacts calmly, appropriately and effectively in an emergency. Acute stress reactions in the immediate aftermath of a catastrophic event, and associated paralyzing anxiety, dissociative or confusional states may impede survival actions. This was well-illustrated in the final report from the MV Estonia disaster, which describes reaction patterns in many survivors which created obstacles to evacuation.[132] The major functional impact of acute stress reactions would be expected in the early stages of a disaster, with symptoms, as defined in ICD-10,[133] typically arising within an hour of exposure to a catastrophic stressor and subsiding within 24-48 hours, even with continued exposure to the stressor. A minority of survivors may experience more chronic disabling symptoms (acute stress disorder and longer-term post-traumatic stress disorder). Follow-up studies of civilian maritime accidents have revealed negative and long-lasting psychological impacts.[134] Studies of stress reactions in military crews exposed to single, but potentially fatal, accidents during peacetime are limited but have consistently shown that more highly screened and trained military members are less likely to experience traumatic psychological sequelae following a disaster than their civilian counterparts.

Systematic studies of a military shipwreck and a collision between two Swedish Navy ships revealed relatively low levels of acute stress reactions and substantially improved outcomes over time.[135,136] In submarines, a Norwegian study of three submarine crews exposed to submerged critical maneuver accidents and submerged collisions again found relatively low levels of acute stress reactions. Identified protective factors included high levels of unit cohesion and problem-focused coping strategies, while habitual emotion-based or avoidant coping styles were associated with increased vulnerability to psychological symptoms.[134] A follow-up study of the 2002 USS Dolphin (AGSS 555) incident (in which the crew were forced to abandon ship in heavy seas following flooding and shipboard fires), similarly found lower rates of peri-traumatic distress and PTSD than would be expected in a civilian population and noted a lack of overt psychological symptoms requiring immediate treatment on crew medical assessment during rescue operations.[137] Comparable findings were reported in studies of the 2005 collision of the USS San Francisco (SSN 711) with an undersea mount[25,138] and the 2007 grounding of the French submarine SNA Rubis.[138] The latter additionally reported anecdotal evidence that, in the immediate aftermath of the accident, the crew did not panic and the majority of the submariners responded automatically as they had been drilled. Exposure to simulated DISSUB conditions over a five-day survival exercise was associated with low levels of self-rated emotional stress, and yielded further evidence of individual personality- and coping style-based resilience and vulnerability factors.[129]

While adverse stress response-related threats to survival may be relatively reduced in DISSUB crews, protective screening, training and team cohesion factors do not afford complete immunity and will not generally extend to riders, who are likely to be more vulnerable to dysfunctional reaction.

Other well-documented factors influencing survival under arduous conditions are good leadership and morale.[132] Maintaining morale may be difficult under DISSUB conditions. The senior survivor must balance extending the endurance of survival stores with the need for activity to keep the crew in the best possible mental state.[69] The will to live is a final intangible but critical factor. The historical record shows that failure of DISSUB survivors to engage with survival and escape efforts is associated with expression of fear, hopelessness and resignation,[4] while knowledge and confidence in survival systems are significant enabling factors.[139] Maximizing submarine crew engagement with SER-related training could significantly enhance their survival prospects.

3.3.2.7 Motor function

Following several days' exposure to mildly hypoxic, mildly hypercapnic and thermally challenging conditions, DISSUB survivors will need to be able to perform a variety of manual tasks to evacuate through escape trunks or into rescue vessels, include turning valves, climbing vertical ladders and upper limb support of body weight. Each of these environmental conditions are known to have singular physiological effects on motor function including degradation of postural stability, grip strength, and endurance, and could potentially impair survival actions in a DISSUB. Evidence for combined effects at anticipated DISSUB levels is limited. Five-day exposure to simulated cold, humid, hypoxic, hypercapnic DISSUB conditions elicited subjective symptom changes and disturbances in postural stability that were statistically but not practically significant to DISSUB survivors, nor was any significant effect on hand-grip strength observed.[72] Complaints of muscle soreness and cramps are common among subjects of DISSUB survival exercises[68,69] but do not appear to be associated with any significant functional impairment. For ethical reasons, it is not possible to simulate the worst credible DISSUB conditions. The potential for more significant effects in a real-life event cannot be excluded. Survivors' injuries may clearly have additional implications for their ability to mobilize and self-assist with extrication.

3.3.2.8 Nutrition, hydration and sanitation

Simulated DISSUB studies have shown that without adequate nutrition and hydration, personnel become debilitated and significantly compromised in their ability to survive while awaiting rescue, during escape, or while waiting for recovery on the surface. They also become increasingly susceptible to development of a number of medical problems including thermal injury, starvation diarrhoea and, most seriously, renal failure.[122] It is anticipated that DISSUB survivors would generally have access to more substantial quantities of food and water from underway food stores and therefore, studies involving starvation conditions would be applicable to the minority of survivors.[130]

Current evidence-based SER standards advocate a minimum requirement of one (1) litre (approx. 1 quart) of water and around 1000 to 1200 Cal per day for each survivor, with increased calorific and fluid requirements under hypo- and hyperthermic conditions respectively.[52] High fat foods are preferred because they minimize CO_2 production and provide a high amount of calories for a relatively small volume of food. While sufficient to support tolerance of DISSUB conditions for a seven-day period without significant functional impairment, provisions meeting these requirements would still be expected to result in dehydration and negative energy balance, with associated loss of weight, including both water and body fat,[68,69,72] and with risk of hypoglycaemia on relatively minimal exertion.[79] Even on-demand access to water during survival exercises has been associated with evidence of dehydration,[68,69] emphasizing the inadequacy of thirst as a guide to water needs and the need for monitoring of survivor fluid intake to ensure adequate hydration. The hypercapnic hypoxic DISSUB environment may promote physiological fluid retention and help to maintain fluid balance.[140]

Some nations, including the United Kingdom, provide specific rations for submarine survival, while others, including the US Navy, rely on food embarked for underway use.[4] Onboard potable water supplies may be augmented by emergency rations and reverse osmosis pumps. Pod posting, where feasible, can provide hot food and fluid replacement when rescue assets arrive.[79] US Navy survival exercises have confirmed the food supply in forward compartment stowages to be sufficient for seven-day survival with imposed loss of refrigeration and cooking capability.[69] Stores of long shelf-life foods may be kept aft as a result of stowage limitations forward, but there is no routine provision for this and in a disabled condition with the forward compartment unavailable, aft survival compartment occupants may not have access to adequate food and water supplies. Supply of emergency stores or rations for aft compartment survivor use has been advocated[69] but not implemented.

In DISSUB conditions, sanitation is difficult to maintain because of fluid restriction, lack of refrigeration and limited sanitation tank volumes. There will not be sufficient water for personnel to take showers or wash extensively. Maintained hand-washing practices after use of the head and before preparation of food, together with appropriate disposal of waste, urine and faecal material, is essential to prevent gastroenteritis. An outbreak of gastroenteritis would significantly increase crew susceptibility to other hazards. When there is a large number of survivors, water requirement for hand-washing alone could be significant. Hand sanitation usage of 800 gallons of water for 90 survivors over seven days was postulated by 2004 US Navy Survivex experience (of a total usage of 1266 gallons), with advocated consideration of alternative provision e.g., non-alcohol based hand sanitisers to conserve finite DISSUB potable water supplies.[69] DISSUB food, water and sanitation management guidance is provided in US Navy Guard Books.

3.3.2.9 Radiation

If a DISSUB situation is caused by, or results in damage to, nuclear propulsion or weapons systems, the crew may be exposed to gamma radiation that can penetrate bulkheads and irradiate survivors within survival compartments. In addition to gamma radiation, DISSUB personnel could be at risk from airborne radioactive fission products if these have leaked into the atmosphere from within the primary containment. This will produce a hazard from both direct alpha/gamma radiation from the airborne material and internal radiation via inhalation/ingestion. USN nuclear-powered submarines are routinely supplied with potassium iodine tablets for prophylactic use in radiation emergencies and with real-time radiation meters to monitor radiation exposures and support survival decision-making. A total dose of 1 to 2 Gray is considered acceptable in relation to the other hazards imposed by a DISSUB situation. A rapidly rising dose rate or a rate of around 200 milli-Grays per hour should initiate escape.[51] Problems with resistance to pressurization were identified in trials of existing US Navy radiation meters, and modifications were advocated to ensure effective performance under the hyperbaric conditions likely to be encountered in a DISSUB situation.[141]

Following rescue, trauma and decompression triage of survivors would take priority over any radiological concerns,[79] but survivors known or suspected to have received high radiation doses (> 2 Gy) should be prioritized for early CASEVAC to definitive medical care after treatment of serious or life-threatening injuries or DCS. Purely irradiated casualties pose no radiation hazard to rescue personnel. Survivors externally contaminated with radioactive fission products can pose a hazard, but this is readily mitigated by simple decontamination procedures.

As evident from Table 2 and Figure 3, nuclear accidents have not dominated the submarine accident record and did not result in any of the 64 DISSUB events. The only reported DISSUB-associated radiation injury was a single fatality of a crewman who attempted to shut down the reactor of K-219 following failure of automatic shutdown processes after an explosion in a missile tube and ensuing uncontrolled fire and flooding. Injurious nuclear accidents are noted to have been limited to operating nations renowned for aging vessels and poor maintenance records. Other than the K-219 event, there is no documented evidence of submarine collisions, fires or flooding resulting in radiation leaks or radioactive contamination, even where the damage to the boat was severe. This is a testament to the safe design, built-in redundancy, and operational effectiveness stemming from a near-zero tolerance of nuclear accidents.

3.3.2.10 Summoning help

Limited endurance of onboard and sea survival capability renders early DISSUB alertment, localization and mobilization of rescue assets key to crew survival prospects. Alertment may be submarine-initiated through reported difficulties prior to sinking; use of standard sonar and underwater telephone systems if still functioning, or battery-powered emergency underwater telephones where fitted; and / or release of indicator devices such as flares, indicator buoys, emergency sonar systems and GPS positioning devices such as Submarine Emergency Position Indicating Radio Beacons (SEPIRBs) and Personal Locator Beacons (PLBs). Report of a distressed submarine may alternatively be provided by other involved or passing vessels, or by activation of Submarine Operating Authority (SUBOPAUTH) SUBLOOK / SUBMISS / SUBSUNK processes[51] in the event of failure of a submarine to comply with designated reporting schedules.

Development and implementation of reliable DISSUB alertment and localization technologies is complicated by risk of compromise to covert submarine operations. Even for collisions involving another vessel, alertment is less reliable than might be expected, as exemplified by the Truculent and Pacocha incidents where involved surface vessels continued underway without giving aid or directly reporting the collision. Submarine operating and corresponding search areas may be vast in the absence of any localizing information and prevailing conditions may further compromise search and rescue efforts, as sadly evident following the recent loss of the ARA San Juan.

3.3.2.11 Sea survival following surface abandonment

The physiological and psychological risks associated with sea survival, including circum-rescue collapse, are identical to those associated with any other maritime surface abandonment event and have been extensively documented elsewhere.[132] DISSUB-specific surface-abandonment capability and survival equipment considerations will be discussed in section 3.4.1.

Although major risk factors can be predicted using historical precedent and scientific research, any factor has a range of possible values and many factors interact. For example, shivering from hypothermia raises metabolic rate and increases oxygen usage and CO_2 production, or the additive or synergistic effects of toxic gases. Ethical constraints limit the extent to which the DISSUB environment can be recreated under experimental conditions. Estimates inevitably involve extrapolation from known data points and a degree of educated guesswork. Unanticipated factors or improbable toxins could be the limiting factors for survival and unquantifiable factors, such as human variability and the will to survive may be key.

3.3.3 Casualty estimate

Historical review of survivable international DISSUB events (n=45) revealed a wide spectrum of potential medical outcomes ranging from no (4.5% events) or minimal injuries to multiple fatalities. It proved difficult to review DISSUB surface abandonment and rescue event data in isolation from escape, as they are not mutually exclusive events. It is common for survivors to be evacuated from the stricken vessel using a combination of methods, particularly where surface abandonment was incomplete before the vessel sank. The only successful nuclear / DE DISSUB rescue event culminated in rescue of all survivors of the inciting incident with no reported injuries beyond being "cold and wet". Dependent on the timing of arrival of rescue assets and rate of deterioration of onboard conditions, all events with an onboard survival phase have potential to culminate in a rescue effort. To mitigate the paucity of onboard health status evolution data from pure rescue events, DISSUB data analysis was therefore extended to all events with an onboard survival phase, including rescues, delayed escapes and failed escape / rescue efforts. Casualty streams, mean fatality and injury incidence rates and phasing determined from the combined data from injurious nuclear / DE DISSUB events with survivors (n=42) are presented in Figure 6.

Data is presented as single injury diagnoses for ease of understanding of the total injury and treatment burden. Thirty-eight percent of casualties had more than one diagnosis, which may present additional medical management challenges in combination than discretely. Significant numbers of survivors (mean 32.6% of the submarine crew; worst case single incident 84%) were recovered from the water following surface abandonment or escape and may have additionally required treatment for immersion syndromes.

In DSVs, injuries and fatalities were mainly due to hypothermic conditions and CO_2 build-up during the onboard survival phase. Two of the 21 DSV rescuees additionally required treatment for DCS.

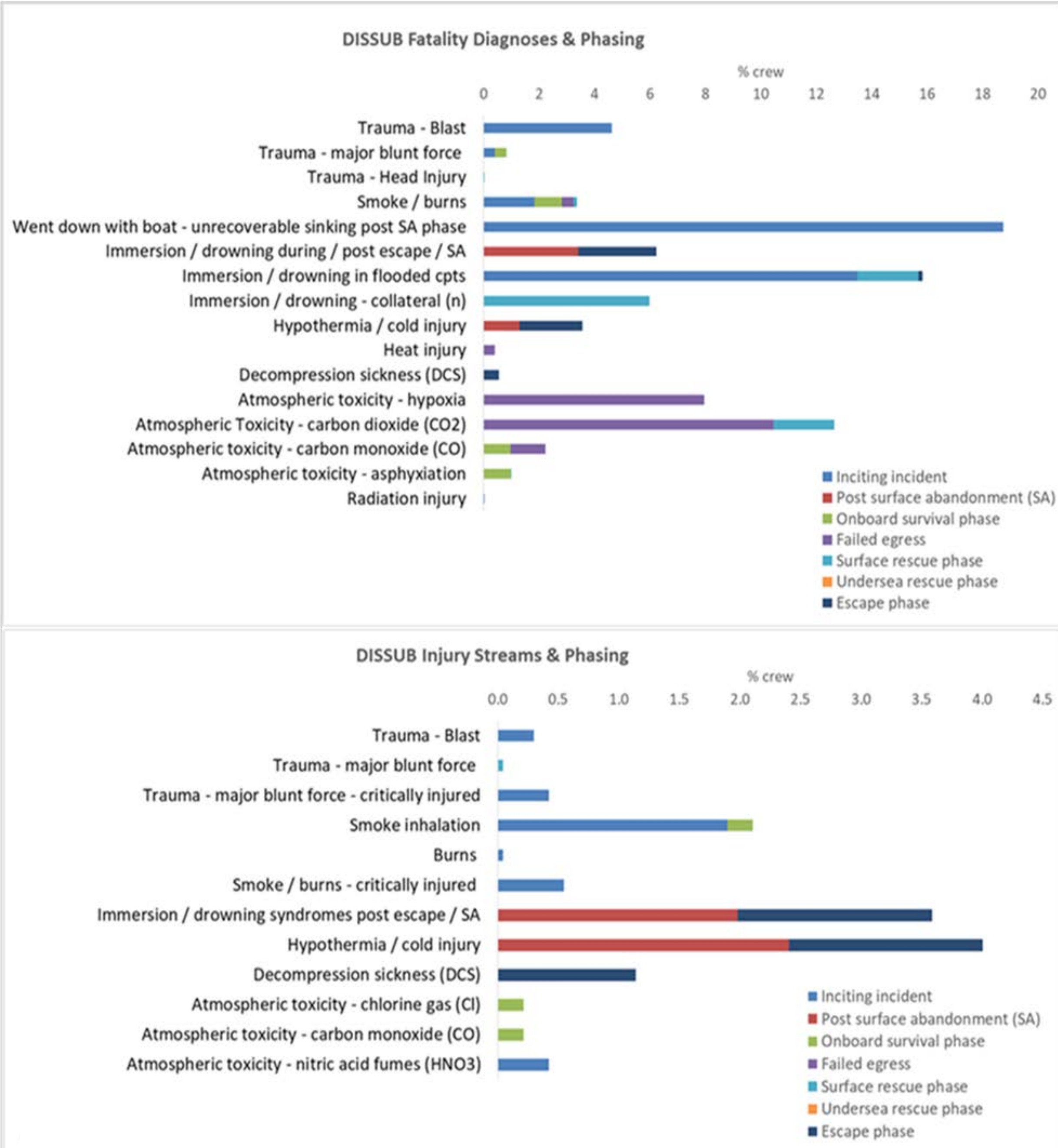

Figure 6: Nuclear / Diesel-electric DISSUB event casualty steams

Table 6: Estimate of medical management burden for USN DISSUB event (surface abandonment/rescue scenarios)

Survivable Nuclear / DE DISSUB	% crew		n=155	
	Average	Worst case	Average	Worst case
Submarine crew fatalities	**56.6**	**100.0**	**88**	**155**
Ultimately fatal inciting incident injuries				
Trauma - major blunt force - died onboard survival phase	0.4	11.5	1	18
Trauma - head injury - died onboard survival phase	0.02	0.7	0	1
Smoke / burns - died surface rescue phase	0.6	22.2	1	34
Acute radiation sickness - died post rescue	0.3	6.4	0	10
Chronic irradiation injury - died post rescue	0.2	12.0	0	19
Injured survivors	**5.7**	**83.7**	**9**	**130**
Trauma - Blast	0.3	12.5	0	19
Trauma - major blunt force	0.0	2.2	0	3
Trauma - head injury	0.1	6.5	0	10
Trauma - spinal	0.0	0.7	0	1
Trauma - fracture / dislocation	0.2	8.0	0	12
Trauma - other major	0.4	16.7	1	26
Trauma - minor	1.4	38.4	2	60
Smoke inhalation	2.1	60.4	3	94
Burns	0.0	2.1	0	3
Immersion / drowning syndromes post escape[1] / SA / man overboard	3.6	83.7	6	130
Hypothermia / cold injury post escape[1]/ SA / man overboard	4.0	83.7	6	130
Hypothermia / cold injury - in DISSUB	0.2	9.6	0	15
Freezing cold injury (freon exposure)	0.6	19.7	1	31
Heat injury	0.4	20.0	1	31[2]
Dehydration	0.2	9.6	0	15
DCS post escape[1]	1.2[1]	44.9[1]	2[1]	70[1]
DCS post pressurized undersea rescue (>60fsw)	5.0[3]	80.0[4]	8[3]	124[4]
Pulmonary oxygen toxicity post pressurized undersea rescue (>60fsw)	>/=10.0[5]	95.0	>/=16	147
Atmospheric Toxicity -CO2	#[6]	#[6]	#[6]	#[6]
Atmospheric toxicity - hypoxia	0.0[7]	0.0[7]	0[7]	0[7]
Atmospheric toxicity - Cl	0.2	15.2	0	23
Atmospheric toxicity - CO	0.2	23.9	0	37
Atmospheric toxicity - freon	0.3	23.9	1	37
Atmospheric toxicity - nitric acid	0.4	8.8	1	14
Atmospheric toxicity - other				
Acute radiation sickness	0.9	29.6	1	46
Chronic irradiation injury	0.9	31.9	1	49
Mental health - acute stress reaction	4.0[8]	20.0[9]	6	31
Mental health - PTSD / adjustment disorder	0.3	12.3	0	19
Reportedly uninjured survivors	**37.7**		**58**	
Recovered from water post Man Overboard / SA - potential immersion syndromes	32.3	96.7	50	150

Color Key:

Estimate derived from DISSUB event data (n=56; total crew = 2436)

Estimate derived from all injurious survivable event data (45 survivable DISSUB + 41 injurious near-miss; n=86; total crew = 6494)

Estimate derived from scientific evidence

Notes:

[1] Escape data limited to events where escape occurring in conjunction with surface abandonment / rescue

[2] Data relates to 24hr exposure to severe heat-stress conditions. Likely conservative for longer duration exposures.

[3] With controlled recompression i.a.w. SRS decompression plan[59]

[4] 5ATA (132 fsw) pressurized DISSUB no recompression facility[83]

[5] Approx. 10% symptomatic hypersusceptibility seen experimentally at threshold exposures[96]

[6] Potential for transient mild symptoms following CO_2 exposures between 3%SE and escape limits

[7] Minimal symptoms anticipated with exposures within escape limits

[8] Acute stress reactions after submarine accidents[137]

[9] General population catastrophic event acute stress reaction incidence rates[135]

Proportional casualty distributions were extrapolated to a crew of 155 assumed for USN DISSUB planning purposes,[59] to provide average and worst-case casualty estimates. It is evident that the majority of injuries in DISSUB events are incurred during the inciting incident and during the sea survival phase of surface abandonment events. Therefore, we looked at wider injurious mishap events as an additional source of inciting incident injury data to support casualty estimates. This also includes more active class event data and may be more reflective of the impact of design and safety program developments on injury risks. Scientific data was additionally used to address gaps in anticipated injury profiles. Resulting estimates of the medical management burden for USN DISSUB rescue and surface abandonment events are presented in Table 6.

Estimates can be adjusted using additionally provided injury rates in crew percentage format, to allow application to differing crew sizes or to take account of significant numbers of embarked riders. Medical contingency planning should also consider the potential for additional collateral casualties from other involved vessels, or among responders. Historically, 3.6% DE / nuclear boat DISSUB and 10.5% of all injurious events have resulted in collateral casualties, with estimates derived from average (for events with collateral casualties) and worst case historical data and predictive modelling of responder DCS risk[59] presented in Table 7. In the absence of a known denominator of total historically or potentially exposed personnel, estimates reflect actual numbers of historically reported casualties.

Table 7: Collateral casualty estimate for international diesel-electric / nuclear DISSUB event

Collateral injuries	n	
	Average[1]	Worst case
Other involved vessel / personnel injuries		
Fatalities	8	63
Trauma - #/dislocation	0	1
Trauma - minor (eye irritation - diesel)	1	5
Smoke inhalation - dockyard workers	2	15
Recovered from water post vessel sinking - potential immersion syndromes	4	26
Responder injuries		
Fatalities	3	10
Smoke inhalation - firefighters	1	7
Acute radiation sickness - firefighters	1	10
Chronic irradiation injury - firefighters	4	39
DCS post pressurized rescue >60fsw - DET, PRM & chamber attendants	2 [1]	

Key:
Estimate derived from DISSUB event data (n=56; total crew = 2436)
Estimate derived from all injurious survivable event data (45 survivable DISSUB + 41 injurious near-miss; n=86; total crew = 6494)
Estimate derived from scientific evidence

Notes:
[1] Per event with collateral casualties
[2] Rescue i.a.w. SRS Decompression plan[59]

A differing injury profile is evident in DSV DISSUB events and an alternative casualty estimate derived from DSV DISSUB data (n=6; total crew 21) is additionally provided in Table 8. This is presented in crew percentage format only due to the greater variability in potential DSV crew numbers.

Table 8: Casualty estimate for international Deep Submergence Vehicle (DSV) DISSUB event

DSV DISSUB	% crew	
	Average	Worst case
Crew fatalities	9.5	50.0
Injured survivors	**90.5**	**100.0**
Hypothermia / cold injury	52.4	100.0
Dehydration	33.3	100.0
DCS	14.3	50.0
Atmospheric Toxicity -CO2	9.5	100.0
Atmospheric toxicity - Cl	14.3	100.0
Reportedly uninjured survivors	**0.0**	**0.0**
Recovered from water - potential immersion syndromes	38.1	100.0
Collateral injuries	**0.0**	**0.0**

The following lessons were identified from the historical record:

a) Rapid notification of a sunken submarine and its location are critical to successful rescue of survivors or recovery of escapers (USS Squalus, HMS Thetis, HMS Truculent, BAP Pachoca, K-141 Kursk).

b) Surface abandonment is a realistic prospect in DISSUB events and may be achievable by the entire ships company even, with assistance, the significantly injured. (HMS Sidon, USS Bonefish (SS 223), BAP Pacocha, USS Dolphin).

c) Unless personnel are in Submarine Escape and Immersion Equipment (SEIE) and rescue assets are on-scene, surface abandonment of a submarine will result in a significant number of casualties due to exposure and drowning (USS Tang (SS 306), USS Bonefish, BAP Pachoca, USS Dolphin).

d) All submarine sinkings with survivors have experienced elevated compartment pressure and progressive flooding (USS Squalus, USS Tang, HMS Thetis, BAP Pachoca, K-141 Kursk).

e) Escape or rescue from a DISSUB, especially if the surviving compartment is pressurized (> 23 fsw) and at a significant depth (> 100 feet), will result in decompression casualties. Without significant recompression assets immediately available on-scene, serious injuries and deaths due to DCI will occur (USS Tang, BAP Pachoca).

f) Submarine fires produce toxic smoke; exposed crew members who do not immediately don EABs will incur significant lung injuries (USS Bonefish, HMCS Chicoutimi, HMS Tireless, USS Tang).

g) Surviving crew and rescuers may incur significant additional injuries in association with damage control and survival equipment use. (HMS Tireless, K-141 Kursk, USS Cochino (SS 345)).

h) A mass casualty event on a submarine will quickly overwhelm onboard medical assets. (USS Tang, USS San Francisco, HMCS Chicoutimi, HMS Turbulent).

i) Serious injuries to submariners at sea usually result in death due to the limited treatment available onboard and the inability to rapidly transfer the injured to a Level 2 or above medical treatment facility. The transfer process itself may result in additional injuries or death (HMCS Chicoutimi, USS San Francisco, HMS Tireless).

j) Consideration should be given to mitigating the risk of adding responders to the casualty burden. (HMS Sidon, USS Cochino, HMCS Chicoutimi).

3.3.4 Data limitations

We acknowledge that our mishap database has gaps. The dispersed nature of available data sources makes exhaustive search difficult and we are aware of at least two mishaps (Dumlupinar 1953 and Remora 2006) that were overlooked until too late for inclusion in our analysis. In some cases, alleged incidents were disputed, so we only included mishaps reported by more than one credible source. It is evident from proportional mishap representation relative to national submarine fleet size that some countries do not admit to incidents or provide incident details. The covert nature of submarine operations makes more generalized underreporting likely. This is particularly the case for DSV intelligence operations and we suspect may in part account for the small numbers of identified mishaps in this class.

As the gravity of the incident diminishes, data quality and availability degrade. We particularly found this to be the case for casualty data. While fatality data was generally well-recorded in the non-classified sources available to us, injury data was much more limited, as is evident from the relatively low determined rates. We suspect under-reporting of all but the most severe injuries and the available records certainly did not extend to transient condition or symptom level, nor was any data available to support evaluation of treatment phase complications. To support quantitative analysis, we had to make numerical inferences from qualitative casualty report ("a few" / "some" / "many") in several cases, predominantly relating to minor injuries, which we tried to mitigate by maintaining a consistent approach. More granular data sources might also allow more than our broad phasing of biomedical evolution.

Our data analysis is limited to basic descriptive statistics and graphical representation of data. Other agencies have used iterative algorithms and other statistical analytical and modelling techniques to further develop casualty projections.[142-144] In future, our determined incidence rates might be used as the foundation for similar development of DISSUB casualty estimate algorithms and medical planning tools.

DISSUB events are thankfully rare and incorporation of a broad timeframe and international data were necessary to support any meaningful analysis. While we have endeavored to provide data break-down and to highlight trends over time, we acknowledge that our extrapolation of wide-ranging historical outcomes may not fully reflect the impact on DISSUB survivability of recent or nation-specific advances in submarine design / operations and SER capability. Our population estimates should be used with discretion for risk assessment by individual submarine-operating nations.

3.4 Current undersea rescue and surface abandonment response capability

Submarine Escape and Rescue (SER) is an internationally organized capability which will involve almost any nation that can provide assistance to the nation that owns the stricken submarine – the National Authority (NA). Response to a DISSUB incident will require the assembly and coordination of a wide range of assets, personnel and organizations to effect successful recovery of survivors as illustrated in Figure 7.

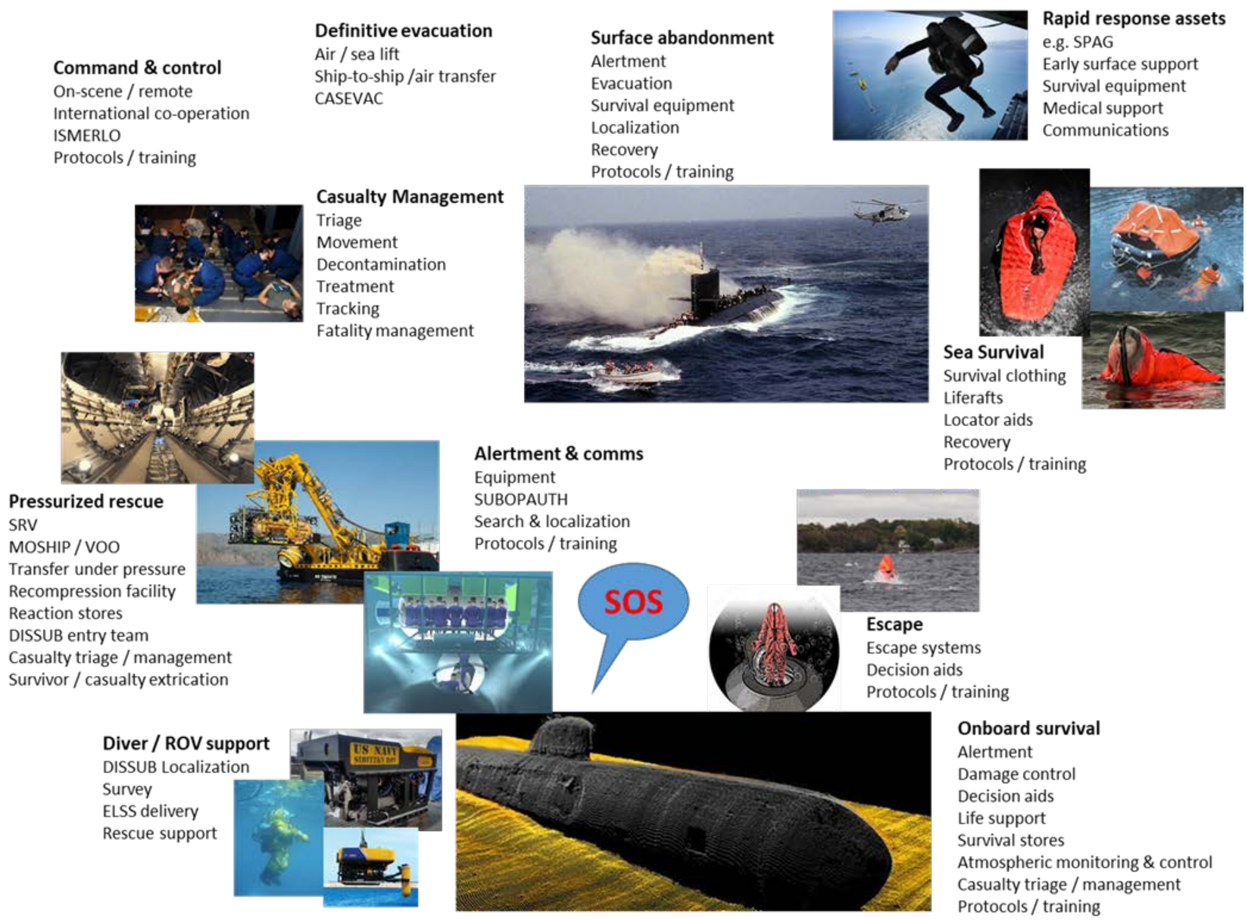

Figure 7. Elements of international Submarine, Escape, Rescue, Abandonment and Survival (SMERAS) capability

Each submarine operating nation is responsible for provision of adequate escape, rescue and survival equipment and procedures for its submariners and additionally provides mutual assistance to other nations when needed, coordinated through the International Submarine Escape and Rescue Liaison Office (ISMERLO) and its live databases of globally available submarine rescue systems and support ships.[145,146] Interoperability and compatibility between rescue systems is also facilitated through collaborative initiatives, the adoption of common NATO-led standards and technical publications[50,51,79] and regular working groups, conferences and international rescue exercises. The following review focuses on current US Navy response capability, including discussion of international assets and collaborative research initiatives which may serve to augment US Navy DISSUB response.

3.4.1 Surface abandonment

If surface abandonment occurs, it is likely to be at the start of a SER operation and efforts should be made to move personnel to a place of greater safety as soon as possible, which in the first instance is likely to be life rafts or passing vessels. Many countries provide suits and equipment which will support enhanced survival of personnel conducting a surface abandonment. For the US Navy, this currently comprises the Mk 10 and Mk 11 Submarine Escape and Immersion Equipment (SEIE) suits, primarily carried onboard submarines to facilitate escape. Both suits consist of an outer suit, a thermal liner, and an integrated single-seat life raft which can be inflated and boarded after escape or surface abandonment. The suits are certified to support 24 hours of survival in conditions ranging from 90ºF sea, 85ºF air, still air and calm sea to 29ºF water, 10ºF air, 30kt wind and sea state 6, with additionally demonstrated effectiveness on thermal evaluation in a US Navy submariner cohort.[147]

US Navy research has demonstrated the compatibility of Mk 10 and 11 suits with conduct of surface evacuation procedures, including water entry from the hull and in conjunction with onboard EAB use.[148] Further R&D efforts to improve surface egress of survivors from a stricken submarine were advocated, together with US Navy extension of routine exercise of abandon ship procedures to submarines and development of a standard for the time in which a full complement of a submarine should be capable of abandoning ship. Arrival of survivors on the sea surface in DISSUB surface abandonment scenarios is likely to be significantly more clustered than would be seen in individual through-water escape and may facilitate localization and recovery of survivors in the absence of any current US Navy PLB capability and raft design limitations precluding lashing rafts together (R Plaisted / D Fothergill PhD e-mail communication 06 Mar 2014; ISEA MCR dated 2/11/2014). Development of infrared reflecting streamers may offer an alternative means of detecting DISSUB survivors in the water and US Coastguard-developed leeway coefficients for Mk-10 life rafts should optimize the efficiency of surface survivor search and rescue operations.[149] There is no current provision of life raft survival stores to extend endurance of sea survival following DISSUB abandonment, with options further limited by the recent removal of portable desalinators from 688 and 774 classes and exclusion of lashing spare rafts loaded with materials to manned rafts by raft design limitations (R Plaisted / D Fothergill PhD e-mail communication 06 Mar 2014).

Maritime Patrol Aircraft (MPA) and international Submarine Parachute Assistance Group (SPAG) capability may play a role in assisting with response in DISSUB surface abandonment events. Currently operated by the United Kingdom, Italy and Turkey, SPAG assets provide rapid response SER expertise and equipment,[79] including rigid-hulled inflatable boats, 25-man life rafts, food, water and medical supplies, continuously maintained on 6-hours' notice-to-move. The team and equipment pods are air-dropped and parachute into the incident site to provide sea survival and medical support to DISSUB survivors on the surface and establish on-scene communications with rescue forces and, where possible, the submarine, pending arrival of a surface rescue ship. Where the incident is outside SPAG aircraft endurance, conditions exceed parachute operating limits, or when other assets can be on scene quickly, the team may deploy with surface support ships to provide on-scene expert advice and assistance.

3.4.2 Emergency communicating and alerting capabilities

Currently available emergency communicating and alerting assets and existing US Navy capability[52] are summarized in Table 9. The US Navy is actively developing research initiatives to improve alertment and DISSUB localization capability, particularly concerning its effective reliance on a single (SEPIRB) alert system which requires manual launch and may not be accessible to survivors. From a communications perspective, procedures and locations to optimize hull-tap communication capability have been evaluated.[150] It is also increasingly recognized that a non-responsive boat may reflect crew incapacitation or communication difficulties rather than a lack of survivors or rescue requirement. Through-hull communications technologies and other rescue risk assessment modalities for use in such circumstances are being explored.[151]

Table 9: Current USN Navy emergency alertment and communicating capabilities

Class	Los Angeles SSN 688	Seawolf SSN 21/22/23	Ohio SSBN/GN 726	Virginia SSN 774
Asset				
Main underwater telephone	Fwd cpt (AN/WQC-2 or 6)	Fwd cpt (AN/WQC-6)	Fwd cpt (AN/BQQ-6B)	Fwd cpt (AN/WQC-2)
Emergency underwater telephone	No	No	All cpts (AN-BQQ-6D)	No
Emergency communication - other	Posted tap code placard and hammer. 1 fwd, 1 aft	Posted tap code placard and hammer. 1 fwd, 1 aft	Posted tap code placard and hammer. 1 fwd, 1 aft	Posted tap code placard and hammer. 1 fwd, 1 aft
Emergency sonar beacon	1 fwd, 1 aft (AN/BQN-13)	1 fwd, 1 aft (AN/BQN-13)	Fwd (AN-BQQ-6E)	1 fwd, 1 aft (AN/BQN-13)
Tethered indicator buoy +/- combined liferaft	No	No	No	No
Expendable communication buoy	No	AN/BRT-1 and 6	AN/BST-1	Fwd. AN/BRT-6
SEPIRB and launch hardware	2 fwd, 2 aft. Release via escape trunk launch tube or 3-inch launcher	2 fwd, 2 aft. Release via escape trunk launch tube or 3-inch launcher	2 fwd, 2 missile, 2 aft. Release via escape trunk launch tube or 3-inch launcher	2 fwd, 2 aft. Release via escape trunk launch tube or 3-inch launcher
PLB	No	No	No	No
Pyrotechnics (flares)	Fwd cpt only. Ejected via 3-inch launcher	Fwd cpt only. Ejected via 3-inch launcher	Missile cpt only. Ejected via 3-inch launcher	Fwd cpt only. Ejected via 3-inch launcher
Signal ejector	Fwd cpt only. Ejected via 3-inch launcher. Not mini-pod capable.	Fwd cpt only. Ejected via 3-inch launcher. Not mini-pod capable.	Missile cpt only. Ejected via 3-inch launcher. Not mini-pod capable.	None

3.4.3 Rescue

Undersea Rescue Command (URC), operated out of San Diego, CA, is the US Navy's official command for worldwide submarine casualty assessment, intervention and rescue. Current URC rescue assets comprise two Submarine Rescue Chamber (SRC) flyaway systems, and the Submarine Rescue Diving and Recompression System (SRDRS).[52,59,79,152]

3.4.3.1 Submarine Rescue Chamber (SRC)

The SRC is a buoyant McCann-style rescue chamber which provides shallow water unpressurized DISSUB (<1.6 ATA) rescue capability. It is capable of rescue to a depth of 850ft which covers all continental shelves and the vast majority of all rescuable water.[4] It is the only proven rescue asset and, other than adaptation to provide Flyaway System capability (SRCFS) and changes to its support systems, is little altered from its USS Squalus rescue days. It is operated from a support ship and winches itself down to the submarine by means of an air motor and downhaul cable attached to a ring on the submarine's escape hatch by divers or an ROV. An air supply, power and communications lines are provided via an umbilical. The upper of two compartments is maintained at atmospheric pressure and contains operators, passengers and controls. The lower is flooded at ambient sea pressure and blown dry after mating to transfer personnel. (URC fact file). It is operated by two crew and can hold up to 6 rescuees at a time. The SRC is limited to operations in a sea state 4 or 5 for rescue and sea state 3 for training. While it can be pressurized and is capable of mating at high DISSUB pressures, it has no Transfer Under Pressure capability and would need to vent to 1 ATA before opening the hatch at the surface.[4]

3.4.3.2 Submarine Rescue and Diving Recompression System (SRDRS)

Deep water (264-2000 fsw), pressurized rescue (up to 5 ATA) capability is provided by the SRDRS. The SRDRS is a fully integrated system consisting of three elements: the Assessment/Underwater Work System (AUWS) and the Submarine Rescue System Rescue Capable- and Submarine Decompression Systems (SRS-RCS and -SDS). The AUWS is the first system mobilized on alertment of a DISSUB event. Its main component is the Sibitsky ROV, in conjunction with a Launch and Recovery System (LARS), flyaway sonar and supporting systems. The ROV system is certified to depths of 2000 ft and will help to localize and establish contact with the disabled submarine, survey the surrounding conditions and clear rescue hatches. It is additionally capable of commencing stabilization of DISSUB conditions for international submarines with decompression-ventilation or Emergency Life-Support Stores (ELSS) pod-posting capability.

The SRS-RCS Pressurized Rescue Module (PRM-1) Falcon is a tethered, remotely operated submarine rescue vehicle, deployed and controlled from a LARS-equipped surface support ship. It is capable of diving to depths of up to 2000ft and mating with a pressurized disabled submarine at up to a 45-degree angle of both pitch and roll. It can transport up to 16 seated rescuees (or a maximum of 3 stretcher cases and 8 seated survivors) under pressures of up to 5 ATA from the DISSUB to the surface. It is manned by two attendants who assist with transfer of submariners into the PRM and control and monitor life-support functions. PRM operations are limited to sea-state 4 for rescue and sea-state 2 for training. A six-hour average PRM sortie time, from launch to readiness for the next sortie, is assumed for planning purposes. Fire and oxygen toxicity risks currently preclude PRM oxygen pre-breathe/breathe capability and holding of rescuees in the PRM is also prohibited due to lack of climatic controls and associated heat injury risk.

The SRS-SDS is a modular flyaway system composed of two 32-rescuee capable recompression chambers, deck mountings and supporting systems to provide hyperbaric treatment of submariners rescued from a pressurized DISSUB. Additional TUP capability, currently undergoing certification, will enable full end-to-end pressurized rescue of DISSUB survivors up to 5 ATA. The SRC and SRDRS are designed for rapid worldwide deployment via air or ground transport and for installation aboard either naval or commercial "Vessels of Opportunity" (VOOs). ISMERLO maintains a global database of all suitable vessels, with individual ships engaged as required for exercises and real-world events. When the scheme is activated, the nearest suitable VOO sails immediately to the designated loading point, loads the rescue system, supporting equipment and personnel and sails for the incident site.

The SRDRS concept of operations[5,54,80] has been developed to support rescue of up to 155 personnel from a pressurized DISSUB, with a global Time To First Rescue (TTFR) target of 96 hours (72 hours for sea trials). At least 10 PRM sorties will be required over several days to rescue a 155-man crew at an assumed optimal rate of 48 seated rescuees every 24 hours. Environmental conditions, significant numbers of stretcher cases and high survivor decompression obligations may impose additional rescue cycle delays.[59]

3.4.3.3 Onboard survival

Rescue tempo assumptions are underpinned by an established seven-day onboard survival capability, with defined survival stores (LiOH canisters / curtains and oxygen candles) and distribution premised on worst-case compartment manning levels.[6] Survival store augmentation requirements when riders are embarked are additionally laid down in policy, but compliance is reportedly inconsistent (personal communication Surg CDR Whybourn, CDR (Ret) Quatroche). Recent onboard survival equipment advances include

- Development of Battelle and Micropore ExtendAir® lithium hydroxide curtains, providing survivors with a more efficient and less hazardous means of controlling carbon dioxide build up.
- Implementation and testing of portable, battery-powered, ruggedized Analox O_2, CO_2, temperature and pressure monitoring devices
- SURVIVEX-demonstrated ability to maintain a breathable atmosphere under DISSUB conditions.[69]
- The introduction and ongoing refinement of Submarine Survival Guides ("Guard Books")[58,153] for each compartment of each class of US Navy submarine, providing survivors

with a single publication to help them manage the situation and to guide decision-making to optimize survival.

The US Navy does not provide specific rations for submarine survival, instead relying on food and potable water supplies embarked for underway use. Reverse osmosis pumps (desalinators) were previously provided to augment potable water supplies, which could additionally be taken in support of surface abandonment, but these were removed from 688 (Los Angeles) and 774 (Virginia) classes after potable water supplies were deemed sufficient to meet seven-day DISSUB survival requirements (personal communication R Plaisted / D Fothergill 06 Mar 2014). This may not have considered the potentially significant demand on water supplies for hand sanitation use[69] in the absence of any alternative provision, or to support potential cooling strategies[127] to mitigate heat stress. US Navy Survivex experience additionally identified the risk of insufficient aft survival compartment access to rations and this remains unmitigated.

3.4.3.4 Medical assets

Medical assets play a variety of roles in a successful rescue operation including command liaison, DISSUB entry, mass casualty response, triage and casualty movement through the continuum of care. Accurate triage and casualty extrication present particular challenges in a DISSUB scenario. Unique to submarine rescue, both trauma and decompression triage categories must be evaluated, with additional consideration of decontamination requirements, and may be complicated by communication barriers between international responders. Efficient triage and rescue efforts may be further compromised by the variable experience of first responders, and efforts to locate and assess potentially unresponsive casualties in a dark, confined and hazardous environment, possibly further impeded by the need for protective over-garments. The adoption of universally accepted NATO triage categories[51] and of a common rescue triage card[154] have addressed some of these issues. US Navy evaluation of emerging technologies to support expedited casualty location, life-death determination and biomonitoring has yet to identify any attractive solutions, but advocates ongoing review to enhance current capabilities.[155] The substantial difficulty associated with assisted extrication of incapacitated casualties from a submarine was hilighted in the Chicoutimi and San Francisco incidents and subsequent capability review.[156] URC continues to explore options for more maneuverable casualty extrication devices and for effective onward movement of potentially large numbers of survivors, in various states of incapacitation, from the VOO.[157]

Pre-planned medical response and integration with the operational plan are key to success and are laid down in medical supplements to NATO[50,79] and US Navy[56] SMERAS plans, and in current rescue system decompression plans.[59] These supply a DISSUB-adapted mass casualty plan and provide a plan to provide medical and recompression treatment of DISSUB survivors to ensure the best outcome for the greatest number and to protect rescue asset operators and medical responders from harm. None of the responses since the Kursk (Chicoutimi, AS-28, San Juan) have been “by the book” rescues and all required impromptu decision-making and special rescue/support plan development. Ability to capture, review and share lessons learned from individual exercises and real life events is critical to continuing evolution of effective SER capability. ISMERLO[146] and the NATO Submarine Escape and Rescue Working Group (SMERWG)[158,159] have proved valuable assets in this regard.

3.4.3.5 Current capability limitations and initiatives

Recent US Navy experience in response to the missing ARA San Juan suggests that TTFR assumptions are not globally achievable with current technologies.[151] Efforts are ongoing to improve DISSUB localization and rescue asset mobilization technologies and to extend onboard survival capabilities without further encroachment on storage space, including passive depressurization and atmospheric decontamination initiatives.[80,151,160] Wider US SER technology objectives[151] include development of shallow water pressurized rescue capability; improving rescue capability in heightened environmental conditions; development of more reliable DISSUB atmospheric monitoring systems;[117] and improved means of assessing risk to rescue forces, particularly in unresponsive / uncommunicative DISSUBs. From a medical perspective, efforts are focused on continuing development of TUP and accelerated oxygen decompression capability and prediction / mitigation of associated DCS and oxygen toxicity risks.[94,95,101,161-164]

Internationally, current NATO SMERWG technical and operational objectives also include further evaluation of onboard survivability endurance against TTFR, together with expansion of knowledge of escape and rescue for a DISSUB lying at an angle; risk assessment of DISSUB hydrogen gas build-up; and development of common DISSUB search procedures and effective supporting communications. Medical panel focus is on update of the ISMERLO website to support implementation of end-to-end casualty tracking; and on development of common clinical protocols and operating agreements.[53,159] SER capability is more generally subject to a range of active international research efforts, with particular focus on extending onboard survival endurance and saturated decompression techniques and complications.

3.5 Capability gap analysis

We identified the following key capability gaps *[and recommended mitigation]* in USN DISSUB surface abandonment and rescue medical response capability:

Onboard survival and medical response

a) Single point-of-failure for DISSUB onboard medical response capability, with effective reliance on the survival and continued fitness for duty of the IDC. *[Crew training]*.

b) The casualty burden and extended onboard treatment requirement in a DISSUB event are likely to exceed modeling assumptions for submarine AMAL and IDC training (holding times of up to 72 hours and mass casualty burden of up to 5 personnel with multiple injuries).[165] *[Training and equipment review]*.

c) Reliability of survivor stay-time calculations. *[Ongoing NSMRL work effort]*.

d) Dependence on unreliable Draeger tube methods for atmospheric monitoring of toxic gases. *[Ongoing NEDU and NSMRL work efforts]*.

e) Limited emergency communications capability between USN DISSUB survivors and rescue forces. *[Improved technologies]*.

f) Lack of USN submarine ventilation / depressurization; BIBS/HP resupply or POD-posting capability *[Improved technologies]*.

Topside medical response

a) Heavy URC focus on lift and recompression capability. Very limited space and supplies to hold and treat conventional casualties. *[Capability review]*.

b) Ill-defined response capability for the surface recovery, triage and treatment of potentially large numbers of survivors in a DISSUB surface abandonment event. *[Policy review]*.

c) Lack of URC AMAL compatibility with space available to accommodate it on Vessel of Opportunity (VOO) or its modularization for immediate use. *[Equipment review]*

d) Lack of standardization of URC Medical Officer jump bags / DISSUB Entry Team (DET) medical equipment. *[Equipment review]*.

e) Delayed certification of TUP Capability. *[Ongoing efforts]*

f) Lack of definitive understanding of decompression injury and oxygen toxicity and their mitigation and treatment risks in DISSUB rescuees *[Ongoing DoN research efforts]*.

g) Lack of effective mechanism for onward movement of survivors from the VOO following initial stabilization and / or recompression treatment. *[Ongoing URC work effort]*.

h) Limitations of available casualty tracking tool, particularly dependence on VOO internet connectivity. *[2018 SMERWG Objective]*.

i) Suggested need for increased USN emphasis on escape capability. Based on historical evidence (particularly the BAP Pacocha and K-141 Kursk experience) and current submarine design (very large numbers of penetrations through watertight bulkheads with testing limited to short duration air pressure drop test during major shipyard overhauls), the authors believe that any DISSUB event will result in rising pressure and slow but unstoppable flooding of the survivor compartment which will require survivors to escape before the minimum rescue force arrival time. *[Top-level policy review]*.

3.6 Application of Prolonged Field Care

The PFC concept aims to optimize survival of the critically injured over hours and days in austere, delayed medical evacuation conditions. It provides a framework for planning medical loadout for support to any mission where space is a planning constraint.[10,166,167] The disabled submarine unquestionably fits all of these descriptors. While the mechanisms and profiles of anticipated injury clearly differ from the operational land environment, we consider there is sufficient overlap in the traumatic and burn-related injuries historically seen in DISSUB scenarios to support relevance of a PFC-based approach.

We accordingly conducted a review of PFC core skills and equipment against USN submarine medical responder training and authorized equipment.[60-62] Prolonged Field Care requires 10 capabilities in at least some capacity, each with defined basic and adjunctive skill levels ("minimum – better – best") over four mission stages from the field medic grab bag to higher echelons of in-theater medical support and evacuation ("ruck – truck – house – plane").[168,169] Exact delineation of these stages is mission-specific.[170] For DISSUB purposes, we felt it reasonable to primarily evaluate onboard medical response capability against "minimum/ruck" level PFC assets, potentially extending to some "better/truck" level capabilities under circumstances where main onboard medical stores are accessible. Higher levels and stages of PFC capability were considered to equate more to rescue authority medical assets.

The remote and covert nature of submarine operations, with limited ship-to-shore, ship-to-ship and air-evacuation capabilities while underway mean that submarine AMALs and Independent Duty Corpsman (IDC) training presume the need to treat and maintain patients for extended periods of time without external support and were found to already incorporate many of the essential PFC skills and equipment. Modeling assumptions (holding times of up to 72 hours and mass casualty burden of up to 5 personnel)[165] are, however, inadequate for anticipated DISSUB requirements and are likely to result in exhaustion of capability prior to arrival of rescue forces.

The following PFC-advocated "minimum" level capabilities and equipment are noted to be deficient from Submarine AMALs or supporting IDC training:

Resuscitate:	Fresh Whole Blood transfusion kits; hypertonic saline
Airway control:	Awake ketamine cricothyroidotomy – lidocaine + ketamine IM
Sedation and analgesia:	Fentanyl Transmucosal (TML); Percocet tablets (PO)
	(Submarine AMAL currently includes only simple analgesics and injectable opiates)

A number of items, which PFC SMEs advocate should be available in the equivalent of the IDC Emergency Response bag, are also currently only in the Submarine general medical AMAL. This could result in additional loss of these minimum level PFC capabilities during a DISSUB event, when one or more compartments are likely to be flooded and access to general medical stores cannot be guaranteed:

Monitoring; Nursing and hygiene: Compact Foley kit

Ventilate and oxygenate:	Positive End-Expiratory Pressure (PEEP) valve for Bag Valve Mask (BVM)
Airway control:	Supraglottic Airway (SGA)
Diagnostics:	Urinalysis test strips; Fluorescein strips
Sedation and analgesia:	Opiate analgesics *(Submarine IDC bag AMAL does not include any analgesics)*

Higher level PFC capabilities include skills such as Rapid Sequence Induction (RSI), sedation and ventilation, diagnostic ultrasound scanning and surgical interventions require constant skill maintenance which is unlikely to be compatible with Submarine IDC and UMO duties and the benefit of incorporating them into training curricula is therefore doubted.

Currently available USN DISSUB emergency medical communications capability would limit potential application of even the most basic level of PFC telemedical support capability to topside medical responders. The same would apply to laboratory capability.

The use of Fresh Whole Blood (FWB) as the resuscitation fluid of choice is strongly advocated by PFC SMEs and is supported by 2014 JTS Committee on Tactical Combat Casualty Care (CoTCCC) guideline change.[171] Recent medical research has provided evidence of the safety, efficacy, and benefits of collecting and transfusing whole blood in the field for Remote Damage Control Resuscitation (RDCR).[172,173] Any delay in massive transfusion is associated with prolonged time to achieve hemostasis and an approximately 5% increase in mortality with each minute blood is delayed.[174] Over-transfusion with crystalloids, the currently available resuscitation fluid on submarines, additionally risks introducing dilution anemia and pulmonary complications.[173,175] Walking blood bank capability is already widely and successfully used in remote military environments[176] and is an existing surface fleet capability.

The benefits, safety and efficacy of PFC-advocated fentanyl and ketamine-based approach to analgesia in austere environments are similarly supported by recent evidence-based guidance[177,178] and SME opinion.[179] Ketamine has recently been added to the submarine AMAL. Oral transmucosal fentanyl citrate (OTFC) is increasingly being adopted by military communities as a safe, effective alternative to morphine for moderate to severe pain in pre-hospital care settings, having the advantages of rapid onset of action and ability to be self-administered and controlled should medical support not be immediately available. The TCCC Triple-Option Analgesia approach incorporating both OTFC and ketamine has gained wide acceptance in the US military and its extension to trauma management in the DISSUB / submarine setting may warrant further consideration.

Success of PFC techniques in the SOF community is assured by cross-training the entire team, a concept which could usefully be extended to optimization of the onboard medical response capability for DISSUB and more generally. The current submarine solution is heavily reliant on the IDC. The IDC is however likely to be quickly overwhelmed in a mass casualty event and may not be numbered among the uninjured survivors of the inciting incident. Onboard training of additional emergency medical personnel is currently limited and ill-defined and subject to individual IDC discretion and capacity. The Submarine EMAT response bag AMAL also suggests that the maximum anticipated submarine EMAT skillset falls significantly short of the minimum advocated for non-medical members of SOF PFC teams.[180,181] A formalized, structured program of appropriate training of additional emergency medical personnel in sufficient numbers to allow some redundancy could significantly help to minimize loss of life and / or compounding of injuries during DISSUB and wider mass casualty events. SUBFOR could potentially avail itself of existing 4-week SOF courses for non-medical personnel, or the curriculum might be used as a structured template for review of onboard training.

More detailed findings of our comparison of DISSUB onboard medical capability against advocated PFC skill and equipment matrices are included in Appendix D.

The URC AMAL was inaccessible for direct review against PFC frameworks. It is currently subject to URC internal review processes to address issues of required update and incompatibility with VOO space constraints. We additionally noted that there is no standard loadout of either DISSUB entry team medical equipment and that the contents of URC team member jump bags is left to individual discretion. From a training perspective, URC's SMO is UMO-trained, consistent with primary role focus on delivery of hyperbaric specialist care. While the current post incumbent is a trauma specialist, trauma or mass-casualty management experience is not pre-requisite for assignment. Nor are any such competencies (or submarine experience) defined for URC IDC assignment, which might be beneficial as the most likely medical member of any DISSUB Entry Team (DET). We suggest that PFC skill and equipment frameworks may be a useful adjunct to review of URC AMALs and role competency and training requirements.

Finally, the Prolonged Field Care Working Group website includes a wealth of downloadable resources[181,182] including triage cards, checklists, and a recently published series of evidence-based clinical practice guidelines providing alternate or improvised management strategies when optimal hospital options are unavailable,[183] which might be adapted for use in a DISSUB scenario.

4.0 Conclusions and recommendations

The potential for survival in a DISSUB event is borne out by the statistical record. Our findings confirm the persistent risk of incidents which threaten further international submarine losses, with human and operational risk factors contributing to mishap risk and severity. There is, however, a strong likelihood that any DISSUB event will occur within rescuable waters and a clear operational and moral imperative to maintain and develop SER capability. SER operations additionally provide significant opportunities for international co-operation and geopolitical benefit, as was exemplified by the recent response to the missing ARA San Juan.

An event that causes the sinking of a submarine is likely to be violent and result in mass casualties. Conventional triage and trauma management capability should be a key component of DISSUB medical response planning.

We have provided an up-to-date overview of current understanding of risks to survival, existing response capability and initiatives, and developed a phased casualty estimate to support medical loadout planning for DISSUB rescue and surface abandonment scenarios. Further work is recommended addressing the escape scenario to enhance understanding of capability gaps across the full spectrum of DISSUB event outcomes. Our casualty estimates could be usefully refined through further efforts to extend the completeness of the mishap database, to identify more granular casualty data sources, and through the application of statistical analytical techniques.

We have identified and suggested mitigation for a number of shortfalls in USN medical response capability, some of which validate existing R&D efforts and objectives, while others warrant additional SUBFOR operator and medical authority consideration. PFC capabilities are undoubtedly relevant to the DISSUB scenario and to wider submarine critical care / mass casualty incidents, with advocated application of PFC principles and skillsets to enhance medical response capability. Investment in DISSUB medical response capability would additionally enhance response to wider submarine and maritime mass casualty events.

Perhaps most significantly, our review of the historical and scientific evidence supports a recommendation for increased focus on enhancing surface abandonment and escape capability. While rescue capability offers the only means of survival for crew trapped in a DISSUB at depths beyond physiological escape tolerance and must be maintained and developed, the historical outcome data in Table 5 suggests that efforts to increase DISSUB survival rates would be directed most profitably at further development of procedures and equipment to improve chances of survival during surface abandonment, through water escape and survival on the sea surface. History has shown that surface abandonment is a realistic prospect and a significant means of survival in catastrophic submarine accidents, including those occurring while operating at depth. Maximizing the potential for evacuation and survival through surface abandonment is also the only option for optimizing survival from a submarine sinking in deep ocean. Based on historical evidence and current submarine design, the authors believe that any DISSUB event will result in rising pressure and slow but unstoppable flooding of the survivor compartment which will require survivors to escape before the minimum rescue force arrival time. This is further compounded by current shortfalls in response capability and supports parallel efforts to optimize escape capability.

We make the following specific recommendations with regard to DISSUB survival and rescue / SA medical response capability:

1) Risk management
   a) Consider implementation of standards and protocols for embarked riders.[*]
   b) Consider further R&D initiatives addressing potential human factors mitigation of submarine mishap risk.[†]

2) Education and training
   a) Encourage / mandate greater engagement with senior survivor training (minimum 5% crew with ensured distribution across different watches and FWD / AFT duty stations).
   b) Implement formalized, structured program of EMAT training with consideration of PFC advocated minimum non-medical member skillsets.

3) Capability review
   a) Review SUBFOR walking blood bank capability requirement.
   b) Consider further evidence-based review of DISSUB and wider SUBFOR analgesia plan.
   c) Consider wider submarine AMAL review based on identified minimum PFC-capability deficiencies.
   d) Explore submarine manning / training options to mitigate potential mishap-related loss / overwhelming of IDC capability.
   e) Consider review of submarine casualty holding-time and mass-casualty modelling assumptions.[169]
   f) Define options / CONOPS for augmentation of URC conventional casualty management capability (e.g., collaborative efforts with other ship / shore-based space and treatment resources).
   g) Consider modularization and standardization of loadout of URC AMAL.
   h) Consider adjunctive use of PFC capability framework to support URC AMAL and role competency / training review.
   i) Consider supply of emergency stores and / or rations for aft compartment survivor use.
   j) Consider alternative hand sanitation provision e.g., non-alcohol based hand sanitizers to conserve finite DISSUB potable water supplies.
   k) Consider provision of pressurization-resistant RADIAC sets.

4) Policy review
   a) Consider SUBFOR development of surface abandonment standards and drills.
   b) Better define responsibilities, capability and CONOPS for medical response to large-scale SUBFOR surface abandonment.
   c) Consider incorporation of DISSUB heat stress risk assessment modalities and escape limits into US Navy policy / CONOPS.

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[*] Rationale: (1) Identified risk factor for mishap occurrence and outcome severity (section 3.1.3 p9); (2) More vulnerable to adverse effects of DISSUB environment (sections 3.3.2.4 p22 and 3.3.2.6 p26); (3) Reduced endurance of survival stores through inconsistent augmentation processes when riders embarked (section 3.4.3.3 p 40).

[†] (1) Predominance of erroneous operator decisions / actions in accident causation (section 3.1.3 p8): (2) Evidence of increased (and increasing) operating risks in non-mission times (section 3.1.1 p7).

5) Further Research and Development (R&D)
   a) Maintain existing R&D efforts addressing:
      i) Reliability of survivor stay-time calculations.
      ii) Development of e-Guard book.
      iii) Reliable DISSUB atmospheric monitoring capability.
      iv) Implementation of TUP capability.
      v) Novel strategies for recompression treatment and accelerated decompression
      vi) Onward movement of survivors / casualties from the VOO.
      vii) Wider PMS 391 technology objectives.
      viii) Mitigation strategies for pulmonary and CNS oxygen toxicity
   b) Consider additional R&D efforts:
      i) To develop a more effective DISSUB casualty tracking tool with offline capability.
      ii) To monitor emerging technologies to support expedited DISSUB casualty location and triage.
      iii) Further SURVIVEX evaluation of new technologies / capabilities.
      iv) Further development of surface abandonment capability.
         1) Efforts to maximize efficiency of full-complement egress with adequate sea survival equipment and stores.
         2) Design / technological initiatives to maximize potential for return to and time stricken vessel can be held at surface.

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6.0 Appendices

APPENDIX A: List of Acronyms

AMAL	Authorized Medical Allowance Lists
AUWS	Assessment / Underwater Work System
BIBS	Built-In-Breathing System
BP	Blood Pressure
BVM	Bag Valve Mask
CAGE	Cerebral Arterial Gas Embolism
CEIs	Cumulative Effect Indices
Cl	Chlorine gas
CNS	Central Nervous System
CO_2	Carbon dioxide
CONOPS	Concept of Operations
CoTCCC	Committee on Tactical Combat Casualty Care
DCI	Decompression Illness
DCS	Decompression Sickness
DE	Diesel-Electric
DET	DISSUB Entry Team
DISSUB	Disabled Submarine
DSRV	Deep Submergence Rescue Vehicle
DSV	Deep Submergence Vehicle
EAB	Emergency Air Breathing systems
EASD	Equivalent Air Saturation Depth
ELSS	Emergency Life-Support Stores
EMAT	Emergency Medical Assist Team
FFP	Fresh Frozen Plasma
FWB	Fresh Whole Blood
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HP	High Pressure air
H_2S	Hydrogen sulfide
IDC	Independent Duty Corpsman
IM	Intramuscular (drug administration)
ISMERLO	International Submarine Escape and Rescue Liaison Office

IV	Intravenous (drug administration)
LARS	Launch and Recovery System
LiOH	Lithium hydroxide
LMA	Laryngeal Mask Airway
LR	Lactated Ringer's solution
LT	Laryngeal Tube
MOSHIP	submarine rescue Mother Ship
MPA	Maritime Patrol Aircraft
N_2	Nitrogen
NA	National Authority
Needle D	Needle Decompression
NG	Nasogastric tube
NH_3	Ammonia
NO_2	Nitrogen dioxide
NRB	Non-Rebreather Mask
NS	Normal Saline
NSMRL	Naval Submarine Medical Research Laboratory
NUMI	Naval Undersea Medical Institute
O_2	Oxygen
OTFC	Oral Transmucosal Fentanyl Citrate
PEEP	Positive End-Expiratory Pressure
PFC	Prolonged Field Care
PLB	Personal Locator Beacon
PMS391	NAVSEA Submarine Escape and Rescue Program Office
PO	Oral (drug administration)
PO_2	Partial pressure of oxygen
PO_2T	Pulmonary Oxygen Toxicity
PRBC	Packed Red Blood Cells
PRM	Pressurized Rescue Module
R&D	Research and Development
RDCR	Remote Damage Control Resuscitation
RH	Relative Humidity
ROV	Remotely Operated Vehicle
RSI	Rapid Sequence Induction
SEALs	Submarine Escape Action Levels
SEIE	Submarine Escape and Immersion Equipment
SEPIRB	Submarine Emergency Position Indicating Radio Beacon

SER	Submarine Escape and Rescue
SEV	Surface Equivalent Value
SGA	Supraglottic airway
SI	Surface Interval
SME	Subject Matter Expert
SMERAS	Submarine Escape, Rescue, Abandonment and Survival
SMERWG	Submarine Escape and Rescue Working Group
SO_2	Sulphur dioxide
SOF	Special Operations Forces
SOFMED	Special Operational Forces Medical
SPAG	Submarine Parachute Assistance Group
SRC	Submarine Rescue Chamber
SRCFS	Submarine Rescue Chamber Flyaway System
SRDRS	Submarine Rescue Diving and Recompression System
SRS-RCS	Submarine Rescue System - Rescue Capable System
SRS-SDS	Submarine Rescue System - Submarine Decompression System
SRV	Submarine Rescue Vehicle
SSBN	Nuclear-powered ballistic missile submarine
SSGN	Nuclear-powered guided missile submarine
SSN	Nuclear-powered attack submarine
SUBFOR	Submarine Force
SUBOPAUTH	Submarine Operating Authority
SUBSAFE	US Navy Submarine Safety Program
SURVIVEX	Survival Exercise
TCCC	Tactical Combat Casualty Care
TML	Transmucosal (drug administration)
TTFR	Time To First Rescue
TUP	Transfer Under Pressure
UMO	Undersea Medical Officer
URC	Undersea Rescue Command
USN	United States Navy
VCO_2	Metabolic carbon dioxide production
VO_2	Metabolic oxygen consumption
VOO	Vessel Of Opportunity

APPENDIX B: Submarine mishap data

DISSUB

Year	Boat	Nation	Class	Type	Location	Incident	Reported activity	Complement (Riders)	Fatalities (Collateral)	Casualties (Collateral)
2017	*ARA San Juan*	*Argentina*	*TR-1700*	*DE*	*South Atlantic off coast of Argentina*	*Unknown*	*Routine patrol*	*44*	*44*	*0*
2013	INS Sindhurakshak	India	Sindhughosh	DE	Naval dockyard off Mumbai coast	Ordnance explosion	At berth	21	18	0
2005	AS-28	Russia	Priz-class DSRV	DSV	Off coast of Petropavlovsk-Kamchatka.	Snagged in fishing nets	Operating at depth 625 fsw	7	0	7
2003	K-159	Russia	November	SSN	Barents Sea	Flooding	Under tow	10	9	0
2000	K-141 Kursk	Russia	Oscar-II	SSN	Barents Sea	Ordnance explosion + later SCOGS flash fire	Not recorded	118	118	0
1989	K-278 Komsomolets	USSR	Mike	SSN	Noweigian Sea 180km south of Bear Island	High pressure air line rupture + flash fire	Transitting back to base	67	42	25
1988	BAP Pacocha	Peru	Balao	DE	Off port of Callao	Collision: rammed by trawler Kiowa Maru	Surface transit	49	8	41
1986	K-219	USSR	Yankee	SSBN	Atlantic Ocean 800km E of Bermuda	Ordnance explosion	Not recorded	113	4	10
1983	K-429	USSR	Charlie-I	SSN	Sarannaya Bay S of Petropavlovsk-Kamchatsky	Flooding seq valve misalignment	Not recorded	100	16	0
1981	S-178	USSR	Whiskey	DE	Golden Horn Bay, off Vladivostok	Collision: cargo ship Refrizherator	Surface transit	59	28	0
1973	Johnson Sea Link	US	Link DSV	DSV	15nm from Key West, FL	Entanglement in cable of sunken ship	Conducing fish trap recovery	4	2	2
1973	Pisces III	Canada	Pisces DSV	DSV	150nm SW of Cork, NI.	Towline fouled on hatch	Recovery to support ship	2	0	2
1971	HMS Artemis (P449)	UK	Amphion	DE	Alongside HMS Dolphin, Gosport	Flooding through torpedo hatch	Refueling	61	0	0
1970	K-8	USSR	November	SSN	Bay of Biscaya, Barents Sea	Fires seq short circuits + flooding during recovery opn	Large scale Naval exercise	133	60	0
1970	Eurydice	French	Daphne	DE	Mediterranean off Cape Camarat	Im- / Explosion of unknown cause.	Conducting dive	57	57	0
1970	USS Bugara (SS 331)	US	Balao	DE	Off Cape Flattery, WA	Flooding	Under tow as target ship	0	0	0
1969	USS Guitarro (SSN 665)	US	Sturgeon	SSN	Mare Island Naval shipyard	Flooding though open hatches	Maintenance activity	0	0	0
1968	USS Scorpion (SSN 589)	US	Skipjack	SSN	North Atlantic Ocean 650km SW of Azores	Unknown catastrophic accident	Transit	99	99	0
1968	DSV Alvin (DSV 2)	US	DSV-2	DSV	Atlantic Ocean 88nm S of Nantucket Island	Uncontrollable flooding through open hatch	Dispatch from support ship	3	0	3
1968	K-129	USSR	Golf-II	DEB	Pacific NW of Oahu	Unknown	On patrol	83	83	0
1968	INS Dakar	Israel	T	DE	Mediterranean	Unknown	Not recorded	69	69	0
1968	Minerve	France	Daphne	DE	25nm from base in Toulon	Unknown	Not recorded	52	52	0
1963	USS Thresher (SSN 593)	US	Thresher	SSN	350nm E of Boston, 160km E of Cape Cod	Catastrophic flooding and power loss	Post-overhaul dive trials	106 (+23)	129	0
1962	B-37	USSR	Foxtrot	DE	Ekaterinsky Bay, Polarny Naval Base	Fire torpedo cpt during maintenance /testing	At berth	59	59 (+63)	0
1961	S-80	USSR	Whiskey	DE	Barents Sea	Flooding through ice-jammed diesel engine air intakes	Operating at snorkel depth	68	68	0
1958	USS Stickleback (SS 415)	US	Balao	DE	Off Hawaii	Collision: hit astern by escort destroyer USS Silverstein	Conducting ASW exercise	81	0	0
1957	M-256	USSR	Quebec	DE	Gulf of Finland, Baltic Sea	Engine explosion / fire	Not recorded	45	38	0
1956	M-200	USSR	Quebec	DE	Returning from Paldiski near Talinn	Collision: hit by destroyer escort	Taking station alongside escort	42	36	0
1955	HMS Sidon (P259)	UK	S	DE	Portland Harbor	Ordnance explosion	Alongside	56	12 (+1)	7
1951	HMS Affray (P421)	UK	Amphion	DE	17 miles NW of Alderney	Flooding through metal fatigued break in snort	Conducting training exercise	75	75	0
1950	HMS Truculent (P315)	UK	T	DE	Thames Estuary	Collision: tanker Davina	Surface running during sea trials	61 (+18)	64	15
1949	USS Cochino (SS 345)	US	Balao	DE	100nm N of Hammerfest, Norway	Battery explosion / fire seq water ingress	Conducting training exercise	81	1 (+6)	22
1945	HMS XE-11	UK	XE class mini-sub	Midget	Loch Striven, Scotland	Collision: struck by merchant ship	Not recorded	2	0	2
1945	U-2344	Germany	XXIII	DE	Baltic Sea 54.16'00"N 11.48'30"E	Collision: submarine U-2336	Conducting sea trials	14	11	0
1944	U-1234	Germany	IXC	DE	Baltic Sea	Collision: struck by tug Anton.	Conducting sea trials	48	13	0
1944	U-2	Germany	IIA Coastal	DE	W of Pillau (today's Baltiysk, Russia)	Collision: trawler Helmi Sohle	Not recorded	35	17	0
1944	U-2331	Germany	XXIII	DE	Off Hel Peninsula in Baltic Sea	Dive system malfunction	Undergoing fast-track work-up	19	15	0
1944	U-28	Germany	VIIA	DE	Off Neustadt	Collision: dummy freighter	Conducting training exercise	44	0	0
1944	U-7	Germany	IIB Coastal	DE	W of Pillau	Dive system malfunction	Not recorded	25	25	0
1944	U-737	Germany	VIIC	DE	Vestfjorden, 68.09'N15.39'E	Collision: German ship MRS25.	On patrol	51	31	0
1944	USS S-28 (SS-133)	US	S-Class	DE	Off Oahu	Unknown	Conducting ASW exercises	42	42	0
1944	USS Tang (SS 306)	US	Balao	DE	Formosa Strait	Flooding seq circular run of own torpedo.	In pursuit of Japanese troopship	87	78	5
1944	USS Tullibee (SS 284)	US	Gato	DE	N of Pillau	Flooding seq circular run of own torpedo.	War patrol	60	59	0
1943	HMS X-3	UK	X-class mini-sub	Midget	Loch Striven, Scotland	Flooding seq engine cooling water hose failure	Conducting submergence trials	3	0	3
1943	Delfino	Italy	Squalo	DE	1 hour out of Taranto	Collision: escort ship	Leaving port	52	28	0
1943	HMS Untamed (P58)	UK	U-Class	DE	Off Campbeltown, England	Flooding seq valve indicator malfunction	Conducting exercises	31	31	0
1943	HMS Vandal (P64)	UK	U-Class	DE	1.5nm N of Loch Ranza, off Isle of Arran	Flooding ?cause of aft cpts.	Conducting sea trials	31	31	0
1943	U-34	Germany	VIIA	DE	Baltic 55.42'N21.09'E	Collision: U-Boat tender Lech	Not recorded	43	4	0
1943	U-346	Germany	VIIC	DE	Danzig Bay in the Baltic Sea	Crash dive seq mechanical fault	Conducting diving trials	16 (+27)	37	0

Year	Boat	Nationality	Class	Type	Location	Incident	Reported activity	Complement (Riders)	Fatalities (Collateral)	Casualties (Collateral)
1943	U-439	Germany	VIIC	DE	North Atlantic	Collision: submarine U-659	Surface running	49	40	0
1943	U-5	Germany	IIA Coastal	DE	W of Pillau (now Balitiysk in Russia)	Diving accident	Not recorded	37	21	0
1943	U-649	Germany	VIIC	DE	Baltic Sea	Collision: submarine U-232	Conducting training exercise	46	35	0
1943	U-670	Germany	VIIC	DE	Baltic Sea off Keel	Collision: target ship Bolkburg	Conducting training exercise	43	21	0
1943	U-718	Germany	VIIC	DE	Near Bornholm in Baltic Sea	Collision: rammed by submarine U-476	Conducting training exercise	50	43	0
1943	U-733	Germany	VIIC	DE	Outside Gotenhafen Port	Collision: Vorpostenboot V313	Not recorded	46	0	0
1942	U-254	Germany	VIIC	DE	North Atlantic patrol	Collision: struck broadside by submarine U-221	During convoy attack	44	40	0
1942	U-272	Germany	VIIC	DE	Not recorded	Collision: submarine U-634	Conducting training exercise	31	12	0
1942	U-612	Germany	VIIC	DE	Off Danzig in eastern Baltic	Collision: rammed by submarine U-444	Conducting sea trials	45	2	0
1941	HMS Umpire (N82)	UK	U-Class	DE	North Sea	Collision: struck by ASW trawler	Transitting in convoy	33	17	9
1941	U-580	Germany	VIIC	DE	Baltic Sea	Collision: target ship Angelburg	Conducting exercises	44	12	0
1941	U-583	Germany	VIIC	DE	Baltic Sea	Collision: submarine U-153	Not recorded	45	45	0
1940	U-15	Germany	IIB Coastal	DE	North Sea at Hoofden	Collision: rammed by torpedo boat Iltis	Not recorded	25	25	0
1940	U-57	Germany	IIC	DE	Brunsbuttel NW of Hamburg	Collision: Norwegian ship Rona	Conducting training exercise	25	6	0
1939	HMS Thetis (N25)	UK	T	DE	Liverpool Bay,165 nm N of Great Ormes Head	Flooding seq inadvertent open of torpedo tube door	Conducting sea trials	48 (+57)	101	0
1939	USS Squalus (SS 192)	US	Sargo	DE	Atlantic Ocean	Flooding through open hatch seq indicator malfunction	Conducting sea trials	59	26	0

Near-miss (external aid requirement)

Year	Boat	Nationality	Class	Type	Location	Incident	Reported activity	Complement (Riders)	Fatalities (Collateral)	Casualties (Collateral)
2014	INS Sindhuratna	India	Sindhughosh	DE	Off Mumbai	Fire in battery cpt	Conducting sea trials	52	2	7
2011	K-84 Ekaterinberg	Russia	Delta-IV	SSBN	In dry dock at Murmansk	Fire seq welding activity	Maintenance	140	0	0
2010	INS Sindhurakshak	India	Sindhughosh	DE	Alongside in Vinsakhapatnam	Explosion / fire in battery cpt seq faulty battery valve	Alongside	68	1	2
2008	K152 Nerpa	Russia	Akula II	SSN	Peter the Great Gulf, Sea of Japan	Inadvertent activation of fire suppressant system	Conducting sea trials	81 (+127)	20	41
2007	HMS Tireless (S88)	UK	Trafalgar	SSN	N of Deadhorse in Prudhoe Bay Alaska	SCOGS explosion	Training exercise	130	2	1
2007	HMAS Farncomb	Australia	Collins	DE	Asian waters	Propeller entangled in fishing lines	Routine operations	60	0	5
2006	USS Minneapolis-St Paul (SSN 708)	US	Los Angeles	SSN	Plymouth	Flooding through FWD escape trunk seq man overboard	Leaving port	134	2	3
2005	USS San Francisco (SSN 711)	US	Los Angeles	SSN	364nm southeast of Guam	Collision: sea mount	Operating at depth 525 fsw	138	1	114
2004	HMCS Chicoutimi	Canada	Victoria	DE	100 miles NW of County Mayo, Ireland	Electrical fire seq water ingress through open hatches	Surface running repairs	48	1	29
2002	USS Dolphin (AGSS 555)	US	Dolphin	DE	100nm off coast of San Diego, CA	Flooding seq torpedo tube door gasket failure	Surface snorkeling	43	0	7
2001	USS Greeneville (SSN 772)	US	Los Angeles	SSN	9nm off coast of Oahu, Hawaii	Collision: Fishery training ship Ehime Maru	Demonstrating emergency blow	110 (+16)	0 (+9)	0 (+26)
1994	Emeraude	French	Rubis	SSN	Mediterranean off Toulon	Condenser explosion	Engaged in ASW exercise	66	10	0
1989	K-131	USSR	Echo-II	SSN	Norwegian sea off Kola Peninsula	Catastrophic fire seq short circuit	Transitting back to base	109	13	0
1989	K-192	USSR	Echo-II	SSN	Norwegian Sea, 100km NW of Senja in Troms	Partial core meltdown seq coolant leak	Transitting back to base	104	0	4
1988	USS Bonefish (SS 582)	US	Barbel	DE	160nm off Atlantic Coast of Florida	Explosion/flash fire seq seawater leak into battery cpt	Submerged on exercise	92	3	89
1985	USS Swordfish (SSN 579)	US	Skate	SSN	Off Pearl Harbor	Flooding and fire seq inadequate drain pump repair	Leaving port	87	0	0
1984	K-314	USSR	Victor-I	SSN	Sea of Japan	Collision: aircraft carrier USS Kitty Hawk.	Not recorded	94	0	0
1983	K-324	USSR	Victor-III	SSN	282nm W of Bermuda	Snagged frigate towed sonar array cable	Not recorded	100	0	0
1981	S-363	USSR	Whiskey	DE	6nm from Karlskrona Naval Base	Ran aground	Not recorded	60	0	0
1978	Not Known	USSR	Not Known	NK	Near Rockall Bank, 225km NW of Scotland	Propulsion system failure.	Not recorded	104	0	0
1973	K-56	USSR	Echo-II	SSN	Peter the Great Gulf, Sea of Japan	Collision: struck by research ship Academician Berg	Surface transit	90 (+36)	27	0
1972	K-377 (?K-64)	USSR	Alpha	SSN	Not recorded	Reactor accident	Conducting sea trials	31	0	0
1972	K-19	USSR	Hotel II	SSBN	700nm from Newfoundland, Canada	Fire seq hydraulic leak	Operating at depth 120msw	125	30	12
1961	K-19	USSR	Hotel	SSBN	N Atlantic off Southern Greenland	Reactor coolant leak	Not recorded	125	23	0
1945	HNLMS O19	Netherlands	O-19	DE	South China Sea en route to Subic Bay	Ran aground: reef	Not recorded	40	0	0
1944	USS Darter (SS 227)	US	Gato	DE	Palawan Passage	Ran aground	Conducting surface attack run	60	0	0
1943	Axum	Italy	Adua	DE	Near the Morea, off Malta	Ran aground	Conducting reconnaissance mission	45	0	0
1942	USS S-27 (SS 132)	US	S-Class	DE	Kuluk Bay area	Ran aground with flooding of battery cpt	On patrol	42	0	0
1942	USS S-36 (SS 141)	US	S-Class	DE	Off Surabaya	Ran aground with flooding of forward battery	On patrol	42	0	0
1942	USS S-39 (SS 144)	US	S-Class	DE	Coral Sea off New Ireland	Ran aground	En route to station	42	0	0

Near-miss

Year	Boat	Nationality	Class	Type	Location	Incident	Reported activity	Complement (Riders)	Fatalities (Collateral)	Casualties (Collateral)
2016	HMS Ambush (S120)	UK	Astute	SSN	Strait of Gibraltar	Collision: fishing vessel	Surfacing on exercise	98	0	0
2016	USS Louisiana(SSBN 743)	US	Virginia	SSBN	Strait of Juan de Fuca, WA	Collision: MSC support vessel	Routine operations	155	0	0
2015	USS Georgia (SSGN 728)	US	Ohio	SSGN	Kings Bay, Georgia	Collision: channel buoy	Entering port	155	0	0
2014	INS Sindhughosh	India	Sindhughosh	DE	Naval harbor Mumbai	Ran aground	Entering port	52	0	0
2013	K-150 Tomsk	Russia	Oscar	SSN	Zvezda shipyard, Sea of Japan	Fire seq welding activity	Maintenance	0	0	0 (+15)
2012	USS Miami (SSN 755)	US	Los Angeles	SSN	Portsmouth Naval Shipyard	Fire seq arson	In refit	0	0	0 (+8)
2012	USS Montpelier (SSN 765)	US	Los Angeles	SSN	Atlantic Ocean off the coast of Jax, FL	Collision: struck astern by Cruiser	Surfacing in ASW training exercise	110	0	0
2011	HMS Astute (S119)	UK	Astute	SSN	Southampton Docks	Active shooter incident	Port visit	98 (+3)	1	1
2011	HMS Turbulent (N98)	UK	Trafalgar	SSN	Indian Ocean 3 hours out of Fujairah, UAE	Catastrophic AC system failure	Surface transit	130	0	26
2011	USS Houston (SSN 713)	US	Los Angeles	SSN	Guam	Broke free of mooring in tsunami	On mooring	134	0	0
2011	HMAS Farncomb	Australia	Collins	DE	20km off coast of Rottnest Island, Perth	Propulsion system failure	Snorting during post refit trials	60	0	1
2011	HMCS Corner Brook	Canada	Victoria	DE	Zuciarte Channel, Nootka Sound, BC	Collision: channel wall	Conducting training exercise	53	0	2
2010	HMS Astute (S119)	UK	Astute	SSN	Off Isle of Skye	Ran aground	Conducting sea trials	98	0	0
2009	HMS Torbay (N79)	UK	Trafalgar	SSN	Eastern Mediterranean	Ran aground	Not recorded	130	0	0
2009	USS Hartford (SSN 768)	US	Los Angeles	SSN	Strait of Hormuz	Collision: LPD USS New Orleans	Not recorded	110	0	15
2009	HMS Vanguard (S28)	UK	Vanguard	SSBN	Mid Atlantic Ocean	Collision: submarine Le Triomphant	Submerged	135	0	0
2009	Le Triomphant	France	Triomphant	SSBN	Mid Atlantic Ocean	Collision: submarine HMS Vanguard	Submerged	110	0	0
2009	Chinese submarine	China	NK	NK	Subic Bay, off coast of Philippines	Collision: towed sonar array	Not recorded	NK	0	0
2008	HMS Superb (S109)	UK	Swiftsure	SSN	Red Sea 80 miles S of Suez Canal	Ran aground: underwater pinnacle	Transitting at depth 250msw	116	0	0
2008	USS Nebraska (SSN 739)	US	Ohio	SSN	Off Oahu	Sailor crushed in hydraulic rudder-ram	Field Day cleaning evolution	155	1	0
2008	INS Sindhughosh	India	Sindhughosh	DE	Off Dhia's Island, 400nm N of Mumbai	Collision: MV Leeds Castle	Surfacing during war-games	52	0	0
2007	SNA Rubis	France	Rubis	SSN	Off Var coast, SE France	Ran aground	Not recorded	70	0	0
2007	USS Newport News (SSN 750)	US	Los Angeles	SSN	Arabian Sea south of Straits of Hormuz	Collision: tanker (Mogamigawa)	Submerged transit	134	0	0
2006	B-414 Daniil Moskovsky	Russia	Victor III	SSN	Moored near Finnish border	Fire outbreak	Moored	100	2	1
2006	USS Nevada (SSBN 733)	US	Ohio	SSN	Strait of Juan de Fuca, WA	Snagged towline	Not recorded	155	0	0
2005	USS Philadelphia (SSN 690)	US	Los Angeles	SSN	Persian Gulf 30nm NE of Bahrain	Collision: MV Yasa Aysen	Surface transit	110	0	0
2003	HMS Tireless (S88)	UK	Trafalgar	SSN	Arctic patrol	Collision: iceberg	Operating at depth 60msw	130	0	0
2003	USS Hartford (SSN 768)	US	Los Angeles	SSN	La Maddalena harbor , Sardinia	Ran aground	Routine maneuvers	110	0	0
2003	HMAS Dechaineux	Australia	Collins	DE	Off coast of Western Australia	Flooding seq seawater pipe burst	Operating at depth	55	0	0
2002	HMS Trafalgar (S107)	UK	Trafalgar	SSN	Fladda-Chain islet, north of Skye	Ran aground	Conducting training	130	0	3
2002	USS Greeneville (SSN 772)	US	Los Angeles	SSN	Off coast of Oman	Collision: LPD USS Ogden	Conducting personnel transfer	110	0	0
2002	USS Oklahoma City (SSN 723)	US	Los Angeles	SSN	East of Strait of Gibraltar	Collision: tanker Norman Lady	Coming to periscope depth	150	0	0
2002	HMCS Corner Brook	Canada	Victoria	DE	Off Nova Scotia	Flooding seq signal ejector tube malfunction	Operating at depth	53	0	0
2002	HMCS Windsor	Canada	Victoria	DE	Off Halifax	Flooding into hydraulic motor	Not recorded	53	0	0
2001	USS Greeneville (SSN 772)	US	Los Angeles	SSN	Port of Saipan, Western Pacific	Ran aground	Entering port	110	0	0
2001	HMS Victorious (S29)	UK	Vanguard	SSBN	Not recorded	Snagged USCG ship in sonar array	Not recorded	135	0	0
2000	HMS Triumph (S93)	UK	Trafalgar	SSN	West of Scotland	Ran aground	Conducting training	130	0	0
2000	HMS Victorious (S29)	UK	Vanguard	SSBN	Firth of Clyde	Ran aground	Surface transit	135	0	0
1998	USS San Juan (SSN 751)	US	Los Angeles	SSN	S of Long Island, NY	Collision: Submarine USS Kentucky	Conducting training	110	0	0
1998	USS Kentucky (SSBN 737)	US	Ohio	SSBN	S of Long Island, NY	Collision: submarine USS San Juan	Conducting training drill	155	0	0
1997	HMS Trenchant (S91)	UK	Trafalgar	SSN	Off western coast of Australia	Ran aground	Operating at depth 200msw	130	0	0
1996	HMS Trafalgar (S107)	UK	Trafalgar	SSN	Off Isle of Skye	Ran aground	Not recorded	130	0	0
1996	USS Tautog (SSN 639)	US	Sturgeon	SSN	Mouth of Pearl Harbor	Ran aground	Conducting personnel transfer	109	0	0
1996	HMS Repulse (S23)	UK	Resolution	SSBN	North Channel off SW Scotland	Ran aground	Leaving port	143	0	0
1995	USS Drum (SSN 677)	US	Sturgeon	SSN	Hong Kong harbor	Collision: cargo ship Sei Bright	Leaving port	109	0	0
1994	Amethyste	French	Rubis	SSN	Mediterranean off French Riviera	Ran aground	Conducting training exercise	70	0	0
1994	USS Sand Lance (SSN 660)	US	Sturgeon	SSN	Mooring at Charlestown Naval Base	Flooding seq valve removal	Maintenance	107	0	0
1993	SNA Rubis	France	Rubis	SSN	Mediterranean off Toulon	Collision: tanker Lyria	Surfacing in anti-collision maneuvers	70	0	6
1993	USS Grayling (SSN 646)	US	Ohio	SSN	Barents Sea	Collision: Russian submarine	Surveillance operations	155	0	0
1992	USS Baton Rouge (SSN 679)	US	Los Angeles	SSN	N of Murmansk, Russia 69.38N 33.46E	Collision: hit from below by submarine Kostroma	On patrol	110	0	0

Year	Boat	Nationality	Class	Type	Location	Incident	Reported activity	Complement (Riders)	Fatalities (Collateral)	Casualties (Collateral)
1991	HMS Valiant (S102)	UK	Valiant	SSN	North Norwegian Sea	Ran aground	Not recorded	116	0	0
1989	HMS Sceptre (S104)	UK	Swiftsure	SSN	Near Lewis	Snagged nets of fishing vessel Scotia	Not recorded	116	0	0
1989	HMS Spartan (S105)	UK	Swiftsure	SSN	W of Scotland	Ran aground	Not recorded	116	0	0
1989	USS Norfolk (SSN-714)	US	Los Angeles	SSN	Thimble Shoals Channel, Hampton Roads	Collision: stores ship USS San Diego	Leaving port	110	0	0
1989	USS Pennsylvania (SSBN 735)	US	Ohio	SSBN	Port Canaveral FL	Ran aground	Entering port	155	0	0
1988	USS Sam Houston (SSBN 609)	US	Ethan Allen	SSBN	Fox Island Washington	Ran aground	Conducting sound testing	140	0	0
1987	USS Daniel Boone (SSBN 629)	US	James Madison	SSBN	James River at Newport News	Ran aground	Post refit trials	143	0	0
1986	HMS Splendid (S106)	UK	Swiftsure	SSN	Northern Fleet training range Barents Sea	Snagged Soviet submarine in sonar array	Not recorded	116	0	0
1986	K-175	USSR	Echo-II	SSN	Pacific Fleet homebase	Explosion in reactor cpt	Not recorded	104	0	0
1986	USS Atlanta (SSN 712)	US	Los Angeles	SSN	Strait of Gibraltar	Ran aground	Submerged transit	130	0	0
1986	USS Augusta (SSN 710)	US	Los Angeles	SSN	Off coast of Bermuda	Collision: Soviet submarine	Not recorded	130	0	0
1986	USS Nathaneal Greene (SSBN 636)	US	James Madison	SSBN	Irish Sea	Ran aground	Not recorded	130	0	0
1986	Not Known	USSR	Not Known	NK	East China Sea 450km NW of Okinawa	Propulsion system failure ? cause.	Not recorded	104	0	0
1985	K-429	USSR	Charlie-I	SSN	Sarannaya Bay S of Petropavlovsk-Kamchatsky	Uncontrolled startup of reactor	Not recorded	100	0	0
1985	USS Plunger (SSN 595)	US	Permit	SSN	Off Southern California	Collision: freighter	Coming to periscope depth	100	0	0
1985	USS Darter (SS 576)	US	Tang	DE	Near Pusan, Korea	Collision: tanker Kansas Getty	Not recorded	85	0	0
1984	USS Bergall (SSN 667)	US	Sturgeon	SSN	Mooring Norfolk VA	Collision: struck by SRV USS Kittiwake	Moored	109	0	0
1982	K-123	USSR	Alpha	SSN	Barents Sea	Reactor damage seq coolant leak	Not recorded	32	0	0
1982	K-432	USSR	Alpha	SSN	Not recorded	Collision: whale	Conducting sea trials	31	0	0
1982	USS Thomas A Edison (SSBN 610)	US	Ethan Allen	SSBN	40nm off Subic Bay, Philippines	Collision: destroyer USS Leftwich	Surfacing on ASW exercises	140	0	0
1982	USS Bonefish (SS 582)	US	Barbel	DE	Pacific	Flooding all 3 main engine spaces	Surface running	77	0	0
1981	HMS Sceptre (S104)	UK	Swiftsure	SSN	Northern waters close to Arctic	Collision: Soviet submarine	Surveillance operations	116	0	0
1981	K-324	USSR	Victor-III	SSN	Peter the Great Bay, off Vladivostock	Collision: submarine	Not recorded	100	0	0
1981	K-45	USSR	Echo-I	SSN	Not recorded	Collision: trawler Novachalinsk	Not recorded	104	0	0
1981	USS Drum (SSN 677)	US	Sturgeon	SSN	Peter the Great Bay off Vladivostok	Collision: Soviet submarine	Not recorded	109	0	0
1980	K-122	USSR	Echo-I	SSN	85nm east of Okinawa	Fire in engine cpt	Not recorded	104	14	0
1979	K-116	USSR	Echo-I	SSN	Bay of Vladimir, Sea of Japan	Partial reactor meltdown seq coolant leak	Conducting sea trials	104	0	10
1978	K-171	USSR	Delta-IV	SSBN	Pacific Ocean	Reactor accident	Not recorded	140	3	0
1978	K-451	USSR	Yankee	SSBN	Not recorded	Fire in turbogenerator cpt	Not recorded	120	0	0
1977	USS Pintado (SSN 672)	US	Sturgeon	SSN	Western Pacific	Collision: Korean Navy ship	On exercise	109	0	0
1977	USS Ray (SSN 653)	US	Sturgeon	SSN	Mediterranean 10nm off coast of Tunisia	Collision: coral mountain	Not recorded	107	0	10
1976	K-22	USSR	Echo-II	SSN	Mediterranean 36.02'.00"N 20.36'.00"E	Collision: frigate USS Voge.	Not recorded	104	0	0
1976	K-47	USSR	Echo-II	SSN	North Atlantic	Fire seq short circuit	Not recorded	104	3	0
1974	USS Pintado (SSN 672)	US	Sturgeon	SSN	Approaches to Kamchatsky Naval Base	Collision: Soviet submarine	Not recorded	109	0	0
1974	USS James Madison (SSBN 627)	US	James Madison	SSBN	North Sea off Holly Loch Scotland	Collision: ? Soviet submarine	Leaving port	143	0	0
1973	K-1	USSR	Echo-II	SSN	Caribbean 21.35'00"N 80.40'.00"W	Collision: Hagua Bank	Not recorded	104	0	0
1973	USS Batfish (SSN 681)	US	Sturgeon	SSN	Charlestown, South Carolina	Ran aground	Leaving port	112	0	0
1973	USS Sturgeon (SSN 637)	US	Sturgeon	SSN	Near St Croix , US Virgin Islands	Ran aground	Not recorded	109	0	0
1972	USS Seahorse (SSN 669)	US	Sturgeon	SSN	Approach to Charlestown	Ran aground	Leaving port	108	0	0
1971	USS Puffer (SSN 652)	US	Sturgeon	SSN	Near Petropavlosk	Collision: hit by diving Soviet submarine	Not recorded	109	0	0
1970	K-108	USSR	Echo-II	SSN	Sea of Okhotsk	Collision: submarine USS Tautog	Operating at depth 45msw	104	0	0
1970	USS Dace (SSN 607)	US	Permit	SSN	Mediterranean	Collision: ? Soviet submarine	Not recorded	105	0	0
1970	USS Tautog (SSN 639)	US	Sturgeon	SSN	North Pacific off Soviet Kamchatka Peninsula	Collision: Soviet submarine K-108	Surveillance operations	109	0	0
1969	USS Gato (SSN 615)	US	Thresher	SSN	Not recorded	Collision: Soviet submarine	Not recorded	129	0	0
1969	K-19	USSR	Hotel II	SSBN	Barents Sea	Collision: submarine USS Gato	Operating at depth 60msw	125	0	0
1969	USS Chopper (SS 342)	US	Balao	DE	Off cost of Cuba	Power loss	Conducting ASW exercise	81	0	0
1968	K-27	USSR	November	SSN	Barents sea	Partial reactor meltdown seq coolant leak	Not recorded	135	9	83
1968	K-140	USSR	Yankee SSBN	SSBN	Naval Yard Severodvinsk	Reactor criticality accident	Undergoing repairs	120	0	0
1968	USS Von Steuben (SSBN 632)	US	James Madison	SSBN	40nm off south coast of Spain	Entanglement in tow cable	Conducting ASW exercise	130	0	0
1967	K-3 Leninsky Komsomol	USSR	November	SSN	Norwegian Sea	Fire in hydraulic system	Transitting to base	105	39	0
1966	USS Tiru (SS-416)	US	Balao	DE	Fredericks Reef, Coral Sea Islands	Ran aground	Not recorded	81	0	0
1966	USS Tucson (SSN 770)	US	Los Angeles	SSN	Mooring at Newport News	Collision: struck by USNS Gililand	Moored	110	0	0
1966	USS Barbel (SS 580)	US	Barbel	DE	Near port on Hainan Island, China	Collision: cargo freighter	Surveillance operations	79	0	0

Year	Boat	Nationality	Class	Type	Location	Incident	Reported activity	Complement (Riders)	Fatalities (Collateral)	Casualties (Collateral)
1965	K-11	USSR	November	SSN	Naval Yard Severodvinsk	Reactor criticality accident	Refueling	124	0	7
1965	USS Medregal (SS 480)	US	Tench	DE	South China Sea	Collision: freighter	Operating at periscope depth	81	0	0
1963	K-33	USSR	Hotel-II	SSBN	The Kattegat	Collision: MV Finnclipper	Surface transit in mist	104	0	0
1963	HMS Tabard (P342)	UK	T	DE	Brisbane, Australia	Collision: wharf	Docking	63	0	0
1963	HMS Tabard (P342)	UK	T	DE	Off Sydney, Australia	Collision: Frigate HMAS Queensborough	At periscope depth on ASW exercises	63	0	0
1962	USS Skate (SSN 578)	US	Skate	SSN	Baffin Bay off Thule, Greenland	Flooding seq leak in seawater circulation system	Operating at depth 400 fsw	84	0	0
1962	USS Thomas A Edison (SSBN 610)	US	Ethan Allen	SSBN	Off East coast of US	Collision: destroyer USS Wadleigh	Shakedown training	140	0	0
1961	K-8	USSR	November	SSN	Barents Sea	Reactor steam generator explosion	Engaged in Naval exercise	104	0	13
1959	S-99	USSR	Whale	DE	Not recorded	Turbine explosion	Conducting submerged turbine tests	54	0	0
1949	USS Bugara (SS 331)	US	Balao	DE	South of Barbers Point, Oahu	Collision: destroyer escort USS Whitehurst	Conducting ASW exercises	81	0	0
1944	U-673	Germany	VIIC	DE	Atlantic convoy N of Stavanger	Collision: submarine U-382	Not recorded	45	0	0

Collateral casualty

Year	Boat	Nationality	Class	Type	Location	Incident	Reported activity	Complement (Riders)	Fatalities (Collateral)	Casualties (Collateral)
1990	HMS Trenchant (S91)	UK	Trafalgar	SSN	Bute Sound off Arran	Snagged nets of fishing vessel Antares	Conducting training	130	0 (+4)	0
1988	HMS Conqueror (S48)	UK	Churchill	SSN	Off Northern Irish Coast	Collision: yacht Dalriada	Not recorded	103	0	0
1985	K- 431 / 314	USSR	Echo-II	SSN	Chazmha Bay Naval Yard, Vladivostok	Reactor accident + thermal / steam explosion	Refueling	0	0 (+10)	0 (+49)
1981	USS George Washington (SSBN 598)	US	George Washington	SSBN	East China Sea 110nm SSW of Sasebo, Japan	Collision: cargo ship Nissho Maru	Operating at periscope depth	112	0 (+2)	0 (+13)

APPENDIX C: Data analysis summaries

DISSUB - Nuclear / Diesel Electric									
CAUSE	ALL	Collision	Explosion / fire	Flooding	Not known	Systems failure	Reactor accident	Grounding	Snagging
	n	n	n	n	n	n	n	n	n
All incidents	56	25	10	14	5	4	0	0	0
Unsurvivable incidents	11	2	2	1	5	1		0	0
Survivable Incidents	**45**	**23**	**8**	**11**	0	**3**	0	0	0
Total crew	**2473**	**1053**	**634**	**687**		**99**			
Initial survivors - # crew	1641	692	481	442		26			
Ultimate survivors - # incidents	40	23	7	7		3			
Ultimate survivors - -# crew	1145	585	341	193		26			
Total fatalities	**1335**	468	300	494		73			
Submarine fatalities	**1328**	468	293	494		73			
Submarine fatalities - Inciting inc ident	832	361	153	245		73			
Submarine fatalities - post inciting incident	496	107	140	249		0			
Collateral fatalities	**7**	0	7	0		0			
Total casualties	**134**	65	64	5		0			
Submarine casualties	134	65	64	5		0			
Collateral casualties	0	0	0	0		0			

SURVIVABLE INCIDENTS - OUTCOME	ALL	Inciting incident fatality	Surface Abandonment	Surface recovery	Immediate escape	Delayed escape	Rescue	Failed escape / rescue	>1 method of crew egress
	n	n	n	n	n	n	n	n	n
Incidents	45	41	33	2	4	7	1	9	11
# crew	**2473**	832	895	132	85	219	33	277	
Initial survivors - # incidents	45		33	2	4	7	1	9	
Initial survivors - # crew	1641		895	132	85	219	33	277	
Ultimate survivors - # incidents	40		33	2	4	7	1	4	
Ultimate survivors - -# crew	1145		812	80	26	194	33	0	
Injurious incidents (fatalities +/- casualties)	43		30	2	4	7	1	9	
Injurious incidents total crew	2346								
Total fatalities	**1335**								
Submarine fatalities	1328	832	83	52	59	25	0	277	
Collateral fatalities	7								
Total casualties	**134**								
Submarine casualties	134		70	22	15	27	0	0	
Collateral casualties	0								

DISSUB - Nuclear / Diesel Electric									
INJURIOUS INCIDENTS - DIAGNOSES & PHASING	ALL	Inciting incident	Post SA	Surface rescue phase	Onboard survival phase	Escape phase	Undersea Rescue Phase	Failed egress	Notes
	n	n	n	n	n	n	n	n	n
Total crew	**2346**								
Total fatalities	**1335**	**832**	**83**	**59**	**23**	**84**	**0**	**254**	
Fatality diagnoses									
Trauma - Blast	110	110							
Trauma - major blunt force	20	10			10*				*10/10=sequelae inciting incident injury
Trauma - Head Injury	1			1					
Trauma - spinal	0								
Trauma - fracture / dislocation	0								
Trauma - other major	0								
Smoke / burns	80	44		3	23*			10	*13/23=sequelae inciting incident injury
Went down with boat - unrecoverable sinking post SA phase	445	445							
Immersion / drowning during / post escape / SA	148		81			67			
Immersion / drowning in flooded cpts	376	320		52		4			
Immersion / drowning - collateral (rescuers)	6			6					
Hypothermia / cold injury	85		31			54			
Heat injury	10							10	
DCS	13					13			
Atmospheric toxicity - hypoxia	189							189	
Atmospheric Toxicity -CO2	300			52				248	
Atmospheric toxicity - Cl	0								
Atmospheric toxicity - CO	53				23			30	
Atmospheric toxicity - freon	0								
Atmospheric toxicity - asphyxiation	23				23				
Atmospheric toxicity - asphyxiation - collateral (rescuer)	1			1					
Atmospheric toxicity - nitric acid fumes	0								
Radiation injury	1	1							
Total fatality diagnoses	**1861**	**930**	**112**	**115**	**46**	**138**	**0**		
Total injured survivors	**134**	52	62	1	10	43	0		34 injured in >1 phase
Injury diagnoses									
Trauma - Blast	7	7							
Trauma - major blunt force	1			1					
Trauma - head injury									
Trauma - spinal									
Trauma - # / dislocation									
Trauma - other major									
Trauma - minor	0								
Smoke inhalation	50	45			5				
Burns	1	1							
Immersion / drowning syndromes post escape / SA	85		47			38			
Immersion / drowning syndromes - collateral									
Hypothermia / cold injury	95		47		10	38			
Heat injury	0								
Dehydration	0								
DCS	27					27			
Atmospheric Toxicity -CO2	0								
Atmospheric toxicity - Cl	5				5				
Atmospheric toxicity - CO	5				5				
Atmospheric toxicity - freon									
Atmospheric toxicity - nitric acid fumes	10	10							
Radiation injury									
Mental health									
Total injury diagnoses	**286**	63	94	1	25	0	0		
Reportedly uninjured survivors	**884**								
Recovered from water - potential immersion syndromes	757		553			204			

DISSUB - DSV / Midget

CAUSE	ALL	Collision	Explosion / fire	Flooding	Not known	Systems failure	Reactor accident	Grounding	Snagging
	n	n	n	n	n	n	n	n	n
All incidents	**6**	1	0	2	0	1	0	0	2
Unsurvivable incidents	**0**								
Survivable Incidents	**6**	1		2		1			2
Total crew	**21**	2		5		3			11
Initial survivors - # crew	**21**	2		5		3			11
Ultimate survivors - # incidents	**6**	1		2		1			2
Ultimate survivors - -# crew	**19**	2		5		3			9
Total fatalities	**2**	0		0		0			2
SM fatalities	**2**	0		0		0			2
Collateral fatalities	0	0		0		0			0
Total casualties	19	2		5		3			9
SM casualties	19	2		5		3			9
Collateral casualties	0	0		0		0			0

SURVIVABLE INCIDENTS - OUTCOME	ALL	Surface Abandonment	Surface recovery	Immediate escape	Delayed escape	Salvage rescue	Failed escape / rescue		
Incidents	6	1		2		3			
Total SM crew	21	3		5		13			
Injurious incidents (fatalities +/- casualties)	6								
Injurious incidents total crew	21								
Initial survivors - # incidents	6	1		2		3			
Initial survivors - # crew	21	3		5		13			
Ultimate survivors - # incidents	6	1		2		3			
Ultimate survivors - -# crew	19	3		5		11			
Total fatalities	2						2		
Submarine fatalities	2						2		
Collateral fatalities	0								
Total casualties	19								
Submarine casualties	19								
Collateral casualties	0								

INJURIOUS INCIDENTS - DIAGNOSES & PHASING	ALL	Inciting incident	Post SA	Surface rescue phase	Onboard survival phase	Escape phase	Rescue Phase	Failed egress	Notes
Total crew	21								
Total fatalities	2								
Fatality diagnoses									
Atmospheric Toxicity -CO2	2				2				
Total fatality diagnoses	**2**								
Total injured survivors	19								
Injury diagnoses									
Hypothermia / cold injury	11				11				
Dehydration	7				7				
DCS	3					1	2		
Atmospheric Toxicity -CO2	2				2				
Atmospheric toxicity - Cl	3				3				
Total injury diagnoses	26								
Reportedly uninjured survivors	0								
Recovered from water - potential immersion syndromes	0								

APPENDIX D: Submarine vs PFC capability comparison matrices

1. Submarine IDC capability

PFC Capability	1. Monitoring	2. Resuscitate	3. Ventilate and oxygenate	4. Control the Airway	5. Sedation and Analgesia	6. Physical Exam and Diagnostics	7. Nursing and Hygiene	8. Surgical Interventions	9. Telemedical Consult	10. Package and Prepare for flight
Minimum	BP Cuff, Stethescope, Pulse Ox, Foley	Fresh Whole Blood Kit	Bag-Valve-Mask with PEEP Valve	Awake Ketamine Cric	Opiate Analgesics titrated through IV	Physical Exam without advanced	Clean*, warm*, dry*, padded, catheterized	Chest tube, cric	Make comms*, present patient and key vitals	Be familiar with stressors of flight
Better	Capnometry	2-3 cases of LR for Burn Resus	O2 Concentrator	Long duration sedation	Sedation with Ketamine/ option of midazolam	Ultrasound and point of care labs	Elevate head of real bed*, debride, washout NG/OG	Fasciotomy, debridement, amputation	Add labs and ultrasound video	Trained in critical care transport
Best	Vital Signs Monitor	PRBC, FFP, Type specific donors	Portable Ventilator	Proficient in Rapid Sequence Intubation	Educated and practiced in multi drug sedation	Experienced and trained in above	Experienced in all nursing care concerns	Trained and experienced in above	Real time video conference	Experienced in critical care transport
Ruck	Pulse Ox, Head Lamp	1 FWB Kit per man, 2 250cc bag NS	BVM with PEEP Valve	Cric Kit, LMA/SGA, lidocaine and ketamine IM	Fentanyl TML, Percocet PO, Ketamine IM/IV	Urinalysis test strips, fluorescein strips	Compact Foley kit, Sterile kerlix, litter padding	Cric, 10g Needle D Scalpel	Cell Phone and call sheet	Have checklist available
Truck	BP Cuff, Stethescope, capnometry, small monitor	Case LR, Additional FWB Kits, 3% Saline	SAVent or SAVE 2	RSI, LMA/SGA, Cric kit ketamine bag IV	Ketamine IV with midazolam	Blood tubes to drop off labs on the way	Padded litter, NG	Sterile Chest Tube Kit with drapes	Cell phone and call sheet, sat phone, radio	Checklist plus flight evac kit
House	Add defibrillation	2 additional cases LR, Case NS, Additional 3% Saline	Impact Vent and O2 bottle	All from above Add Benzo if not available for truck	Same as above	Blood tubes to run labs to local clinic	Real mattress* with head elevated, nursing care kit sleeping bag	Sterile Surgical Kit with Drapes, Gowns and scrub soap	Secure comms, email	Extensive evac kit
Plane**	Take all of above	All of above	Impact vent on O2	All above calculate for flight and double	All above, calculate for flight and double		Padded litter, sleeping bag	10g needle D Chest tube kit Cric kit	Through aircraft	From Above

Color key: IDC trained and equipped with access to IDC Bag alone
IDC trained and equipped if main medical stores accessible
No onboard capability
* Onboard capability but likely to be compromised in DISSUB scenario
** Potential for rescue asset augmentaton of packaging for flight in DISSUB scenario

2. Submarine Emergency Medical Assist Team (EMAT) capability

PFC non-medical team member minimum capability
Proper tourniquet placement**
Packing an inguinal or axillary wound**
Stopping bleeding** and cleaning abdominal evisceration**
Occlusive dressing**
Assessing indications for needle D**
Insertion of needle D**
Preparation & placement of King LT SGA**
Using SSCOR suction** & squid suction
Bagging with BVM**
O2 tank prep inc NRB & nasal canula**
Setting up SAVent
Using the Oxylator
Using the O2 concentrator
Drawing bloods** for labs or istat
Prep and initiation of IV line**
Prep of Foley catheter**
Suprapubic bladder tap**
Cricothyroidotomy**
GCS from cheat sheet**
Taking full set of vitals manually**
Attaching Philips monitor** or Tempus
Using patient care flow sheet
Eldon blood typing card
Preparing equipment for blood transfusion
Making comms* & reporting** with call sheet
Changing wet to dry dressings**
NG tube prep**
Irrigating wound**
Suturing**
Prep of chest tube inc suction**

Color Key: Equipment available in EMAT bag
Equipment available onboard
No onboard capability
* Onboard capability likely compromised in DISSUB
**Capability not supported by defined, consistent EMAT training

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